THE ASSOCIATION OF
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# THE GEOMETRY OF CONICAL PIPES, BENDS AND JOINTS

By W. SELLAR

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# THE GEOMETRY OF CONICAL PIPES, BENDS AND JOINTS.

By W. SELLAR.

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CAST iron pipes, bends and joints of reasonable design can be made to any desired shape; the skill of the patternmaker is the deciding factor.

For pipe bends made of steel plate, the shapes can be produced by hammering or pressing the flat plates into or around former blocks. These blocks are made specially for the purpose and their costs are necessarily charged against the finished article, but unless fair quantities are to be made the costs of production are prohibitive. Consequently, for the production of one or two articles not likely to be repeated in quantities, a special design requiring the smallest number of special tools will have to be evolved.

In the following notes it is endeavoured, without the use of mathematics beyond elementary geometry, to enlarge on a simple principle which can cover practically the whole subject of fabricated pipe bends and joints, whether welded or riveted.

The technique of fabricated steel work is carried out under one or other of the arc welding systems, but if riveted work is preferred for some reason, the subject-matter of the present work will still apply, but the usual margin for laps must be added to the exact shapes.

The constructions hereinafter described can be used as bases for more elaborate or more "finished" work. They can be used also as skeletons on which a solid pattern can be built to take a plastic wood filling or to be trimmed down to give the requisite finished article.

In this edition the text has been revised and a few notes and diagrams have been added on the subject of joining cones to cones.

* * * *

The normal section of a cylinder or circular bore pipe is a *circle*. A section not normal to the axis is not a circle, but the smallest cross dimension of the section surface will always be equal to the diameter of the cylinder, and the longest dimension will range from the diameter of the cylinder to infinity. In short, *the true form of the oblique section of a cylinder is an ellipse.* (See Fig. 1). These facts will be combined and re-stated. Any number of ellipses can be obtained by taking an oblique section through a cylinder, but the *minor axis* of every one of them will be equal to the *diameter* of

the cylinder, and the *major axis* will depend only on the *length* of the section.

An ellipse is *symmetrical* only about the major and the minor axes. Other diameters will give similar halves of the ellipse, but such halves are to the same hand but upside-down—they are not mirror images.

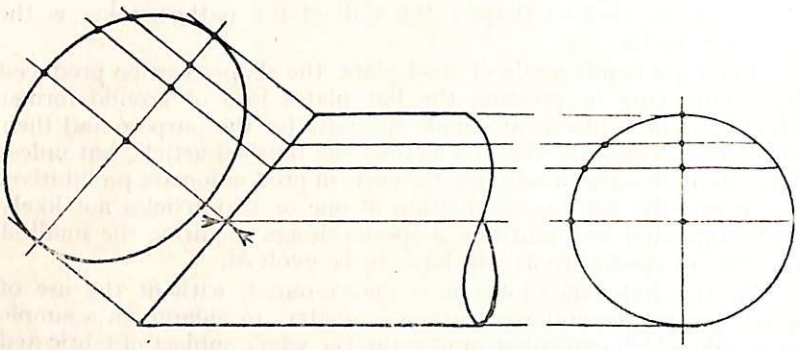

**Fig. 1.**

If two straight pipes of the same diameter are cut obliquely at the same angle, the sections give equal ellipses. These pipes can be joined through their sections in two ways (Fig. 2), one to give a continuous straight pipe (shown dotted), and the other, by relative reversal, to give a knee or elbow.

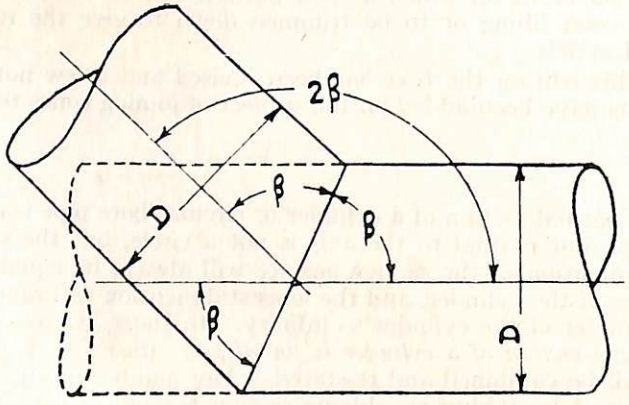


**Fig. 2.**

Figs. 3 and 4 each show two pipes which have to be joined, but it will be observed that the pipes are of different diameters. It will be inferred from what has already been shown, that oblique sections of each pipe can be made to give ellipses having the same *major* axis, but the *minor* axes will obviously be different owing to the unequal diameters of the pipes. A design for ensuring a theoretically correct joint can be devised for a joint of this type and will be dealt with later.

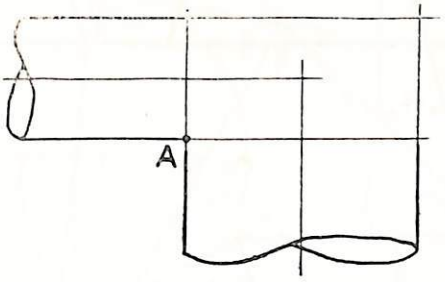


**Fig. 3.**

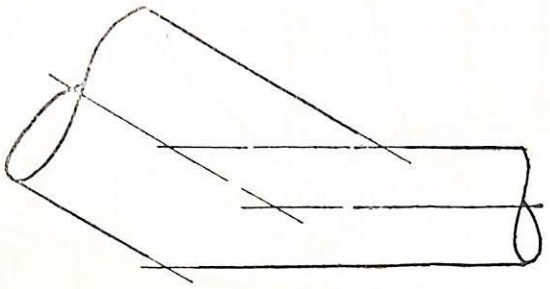

**Fig. 4.**

If a straight pipe is cut up uniformly in sections as shown in Fig. 5, and reassembled alternately, the result will be the fabricated bend indicated in Fig. 6. In this illustrated instance the bend turns through an angle of 90° and the angle $\alpha$ must (see figure) thus be 15°. The angle of a bend may be any angle, and it is only a matter of choosing the angle $\alpha$ judiciously to be assured of the desired result.

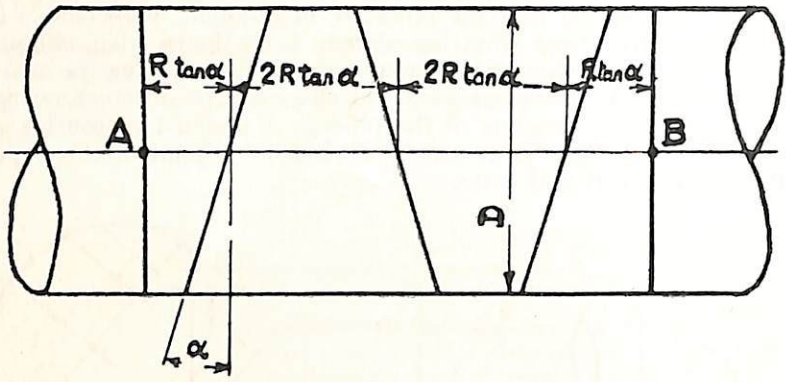
R tanα
2R tanα
2R tanα
R tanα
A
B
α

Fig. 5.

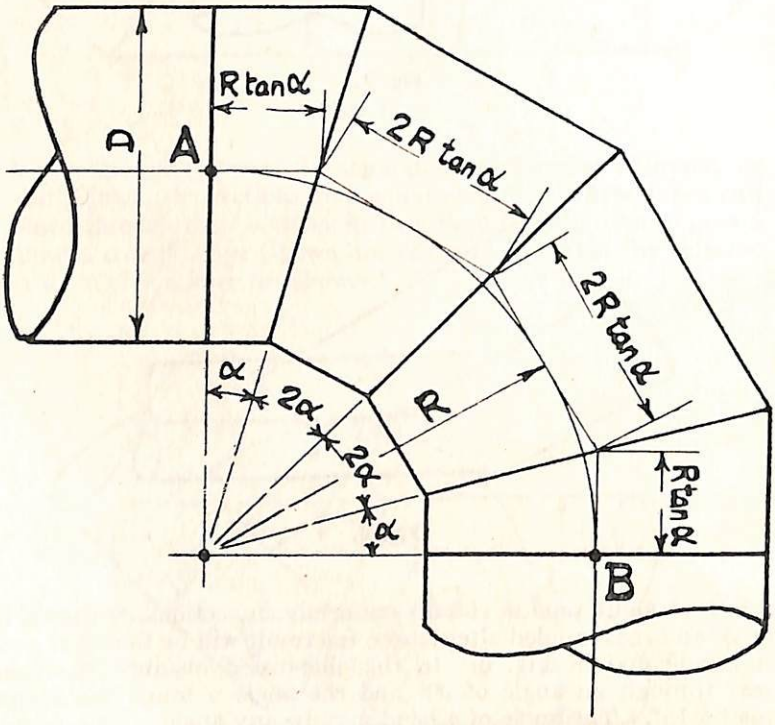
R tanα
2R tanα
A
A
α
2α
2α
α
R
2R tanα
R tanα
B

Fig. 6.

It must be pointed out that a uniform "radius" of bend is possible only if the sections are spaced uniformly, and Fig. 7 should be studied for comparison. This illustration shows a somewhat patched-up article, although the *joints* are theoretically correct.

Sometimes a bend with a long segment in it is necessary, as, for example, in the case where a branch must be provided for without breaking the segment joints. Here the positions of the joints will have to be arranged through the call of commonsense.

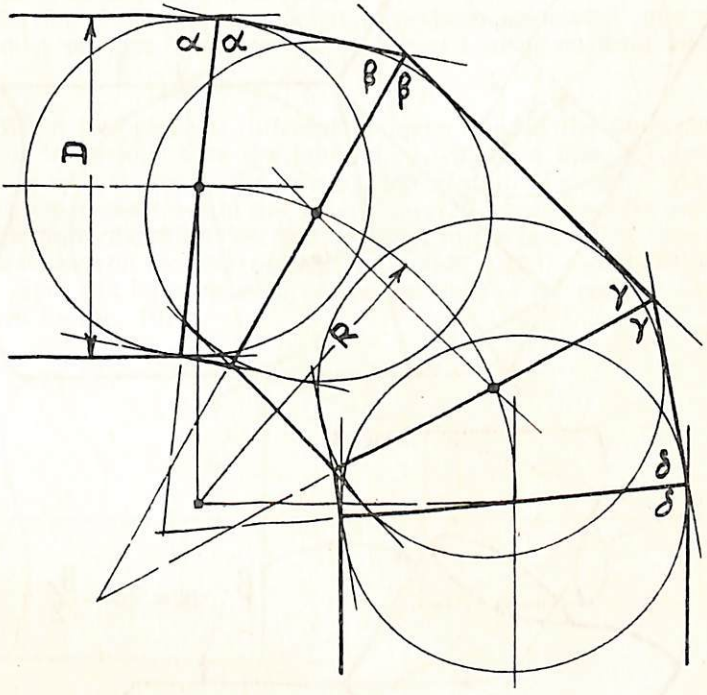


**Fig. 7.**

In some instances it is necessary to remove the sharp outer elbow of Fig. 2. This has been done in Fig. 8. The illustration indicates that if the angle between the two pipes (their bores being equal) is $\beta$, then the angle of the inserted piece ($a$) will be equal to $90° - \beta/2$. Alternatively the insert can be obtained by drawing. The circles shown are drawn with their centres on the pipe axes equidistant from the intersection of the axes, and parallel common tangents are drawn to these circles as shown. Lines joining the intersections of the corresponding lines of course pass through the centres of the respective circles. The angle $a$ is hence obtained by drawing parallels to these lines, as shown also in Fig. 8.

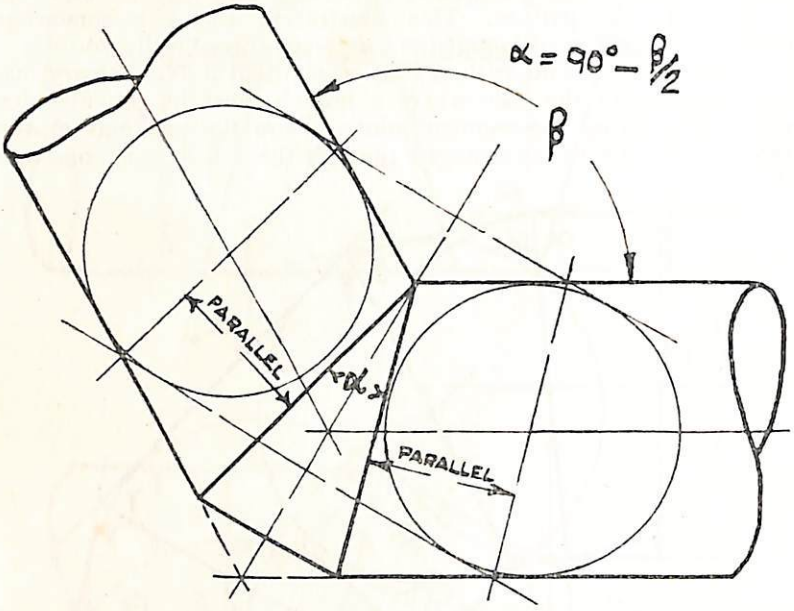


Fig. 8.

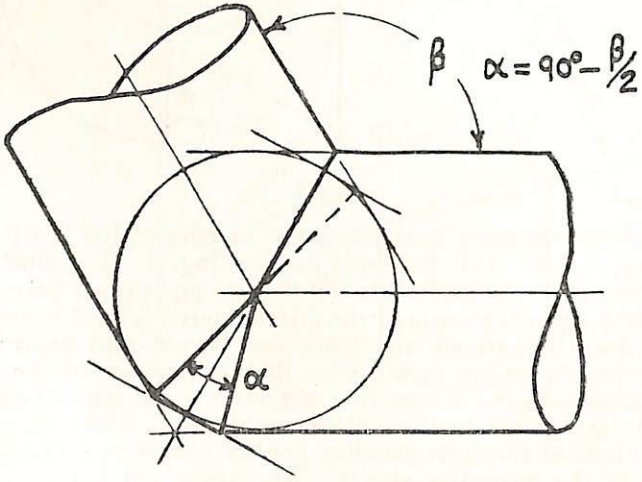


Fig. 9.

The corner above referred to can be cut off in many ways—a special case is shown in Fig. 9. In this instance the auxiliary circles of the previous figure merge into one. If the auxiliary circles spread so far apart (as in their preliminary or constructional position, Fig. 8), then the bend follows the form indicated by the broken lines, a form already discussed (Fig. 7).

Whatever the case may be, the angle $\alpha$ is always $90° - \beta/2$, being the inclination to each other of the oblique sections whereon the auxiliary circles have their circles.

So far the joints considered have been associated only with cylinder sections, but these have a direct bearing on what follows.

* * * *

When two pipes of different diameters lie on the same centre line it is obvious that the joint piece will be a disc, a spherical surface with a hole in the centre, or a frustum of a cone. As the two former cases would not in ordinary circumstances be used as a pipe joint, consideration will be given to the last. The cone will have its axis on the centre line of both pipes, and the joints with the two pipes will be circles, the normal sections of the cone. This is shown in Fig. 10.

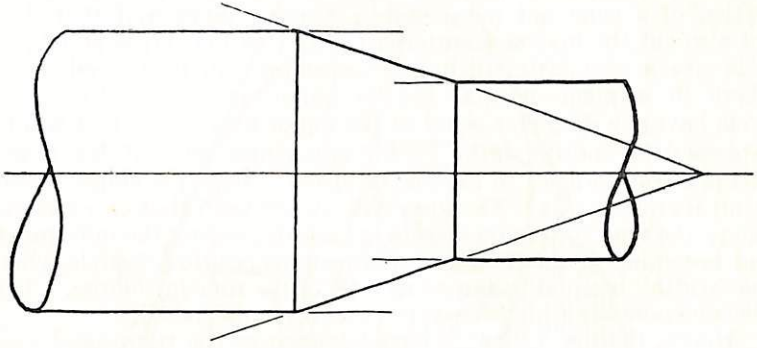

**Fig. 10.**

This device suggests a method of solving the problem indicated by Fig. 3.

Let the end view be drawn (Fig. 11). This gives a small circle whose centre is on the axis of the large cylinder. If *any* normal section ~~AB~~ BC now be taken on the large cylinder *clear* of the small circle, as shown, and two tangents be drawn from the points A C and B to this circle, the tangents will meet at a point ~~C~~ A on the centre line of the large cylinder. This will represent a cone, as a solid figure closing the end of the large cylinder.

The small circle represents the small pipe, and so far as this view is concerned the small pipe cuts away the top part of the cone

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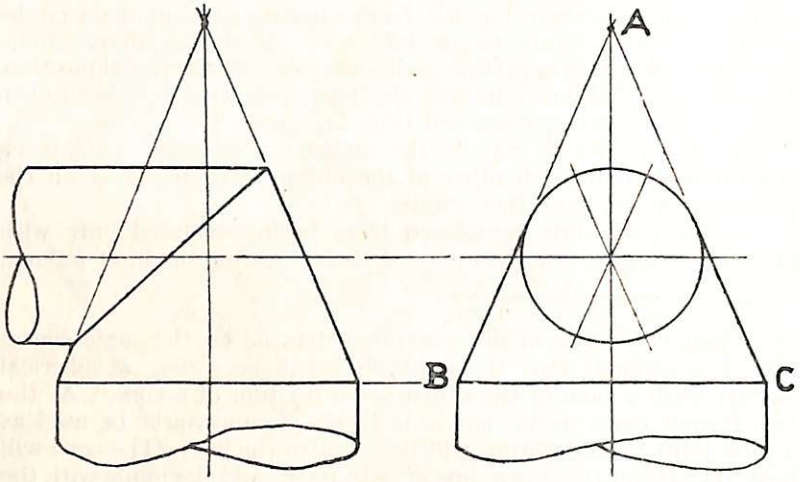


**Fig. 11.**

from the lower part altogether. It is known that an oblique plane section of a cone not parallel to a tangent plane and that does not also cut the inverse counterpart cone (see Fig. 17) is an ellipse. It is also a geometric truth that an ellipse can be viewed somewhere in a plane normal to the minor axis so as to give a circle having a diameter equal to the minor axis. This fact will be expressed in another form. View any ellipse so that the minor axis is at right angles to the line of vision. Turn the ellipse slowly about its minor axis. The form will change from that of a straight line to the true ellipse, increasing in "width" during the movement, and becoming at one definite intermediate position a circle where the "width" is equal to the minor axis of the rotating ellipse. This phenomenon has thus been very carefully emphasised.

Hence, if such a view (a circle) is seen in the right-hand view of Fig. 11 (see also Fig. 1), and the oblique section of the cone is terminated by the sides of the small cylinder, that particular conic section will coincide with the oblique section of the small cylinder, both being ellipses with the same major and minor axes. This reasoning might be unorthodox, but, nevertheless, mathematics being excluded from this work, it should be sufficiently convincing to permit the next step in the subject.

* * * *

Fig. 12 shows a pictorial representation of a *right* cone, that is to say, a cone whose axis AT is perpendicular to the plane of the base. The orthographic projection of this cone would be an isosceles triangle indicated in perspective as ABC. The cone is

cut obliquely by a plane at right angles to the plane of ABC so as to cut both the equal sides of the triangle ABC. To do this the angle of the section plane with the vertical axis AT must never be less than half the angle BAC. The true form of the section thus formed is an ellipse LNM.

Let, now, this cone be cut by two planes parallel to section ABC and equidistant from it so that this ellipse is just touched at the ends of its minor axis. One of these vertical sections is shown shaded in Fig. 12 : these sections are hyperbolas, and they form the sides of a new solid which is in reality the middle portion of the cone ABC.

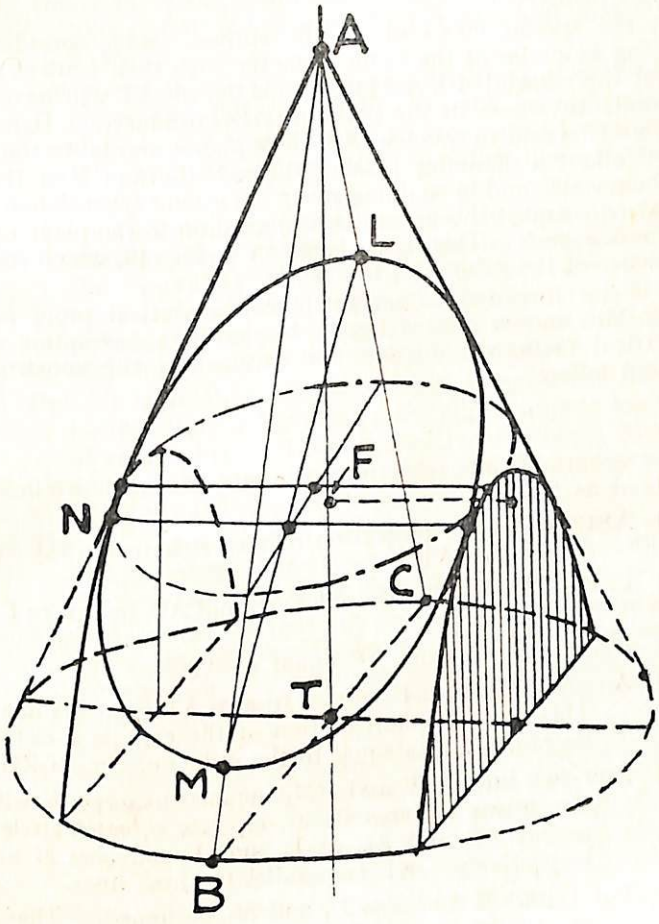


**Fig. 12.**

If this solid now is cut by *any* plane at right angles to section ABC and *touching* both hyperbolas, the resulting section is an ellipse. *Any number of ellipses can be formed under these conditions*, each one having a different major axis, but the *same minor axis*, namely, the distance between the two parallel hyperbolas.

It is clear that there are viewpoints in the plane of ABC produced where all the ellipses referred to in the previous paragraph can appear as circles, each ellipse having its own angle of view in relation to axis AT. And, if the lines of vision in the plane of ABC through the centres of the circles are continued until they cut the vertical axis AT, it will be found that all the points so found will be coincident at F. This common point F is the focus of the hyperbola projected on to the plane ABC.

All the special views of all the ellipses under consideration appearing as circles of the same diameter with their centres at the focus of the associated hyperbola projected on AT will have their viewpoints anywhere in the plane of ABC produced. Hence the circles may be said to revolve with their planes normal to the plane of ABC about a diameter passing through the foci F of the two hyperbola walls, and in so doing *sweep out a solid of revolution which is a sphere.* And if this sphere is projected on to the plane of ABC *the view is a circle.* This figure leads on to Fig. 13, which contains the essence of the subject of this work.

It is not intended to set forth any analytical proof for the relationships shown in this figure, but a short description of the geometrical facts will display the reasons for the constructions that will follow.

* * * *

The essential points relevant to the subject and shown in Fig. 13 are noted as follows :—

(*a*) ABC is a plane projection of any right cone, the vertical axis being AT.

(*b*) Circle GZH touches the sides AB and AC, its centre F being on axis AT.

(*c*) AE is cut off from AC equal to AF.

(*d*) A section through E normal to axis AT cuts this line at D. This normal (plan) section of the cone is a circle, and its radius DE is equal to the radius of circle GZH = FZ.

(*e*) Any two lines UW and $RM_1$ inclined at angle $\alpha$ with AT are drawn as tangents at opposite sides of circle GZH to cut AB and AC at $L_1$ and L and also M and $M_1$ respectively. KF is parallel to these lines.

(*f*) Let L and M and also $L_1$ and $M_1$ be joined. These lines are the major axes of ellipses.

(*g*) KF cuts lines LM and $L_1M_1$ at their mid points N and $N_1$ respectively. (*Note.*—In an oblique section of the cone, N and $N_1$ never fall on axis AT).

(*h*) A normal section through N gives a circle indicated as a semi-circle of radius OP.

(*k*) The semi-chord of this circle drawn through N at right angles to radius OP produced through O is NX (its counterpart is $N_1X_1$).

(*l*) NX and $N_1X_1$ are equal to FG, which is the radius of the circle which determines the position of the hyperbola parallel to plane ABC (Fig. 12).

(*m*) Hence FG is the semi-minor axis of the ellipse whose major axis is LM and also of the ellipse whose major axis is $L_1M_1$.

(*n*) LM giving an ellipse as a section with major axis LM and minor axis GH (*i.e.*, 2 FG) it may be concluded that since L and M are points in two parallel straight lines UW and $RM_1$, these two parallel lines represent a cylinder.

(*o*) Hence, a cylinder, represented by two parallel staright lines touching a circle (or a sphere) hereinafter called the "auxiliary circle" which touches the two lines representing the sides of a cone, will intersect the cone along a straight line which will section the cylinder and the cone with the same ellipse surface.

(*p*) But ML and $M_1L_1$ can be viewed along other directions besides along KF to make the ellipse appear as a circle of radius FG. These cylinders are shown as dotted and broken lines respectively. *But their circles do not touch* AB *and* AC, *the sides of the cone.*

(*q*) The new centre lines of projection pass through N and $N_1$ making angles $\beta$ and $\gamma$ with the planes of the respective ellipses, as in the cases already referred to.

(*r*) The explanation is that the parallel lines representing the new cylinders pass through a counterpart of point F, namely $F_1$, which is found inside the vertically opposite angle of angle BAC. $F_1$ is the focus of another hyperbola (shown in Fig. 17).

(*s*) If the axis of the cylinder intersecting the cone passes through F, there are two common ellipses for the cylinder and the cone, but if the axis does not pass through F (and consequently *must* pass through $F_1$) there is only one* common ellipse. Also, each elliptical

* The vertically opposite cone is not considered with respect to the concrete cone discussed here.

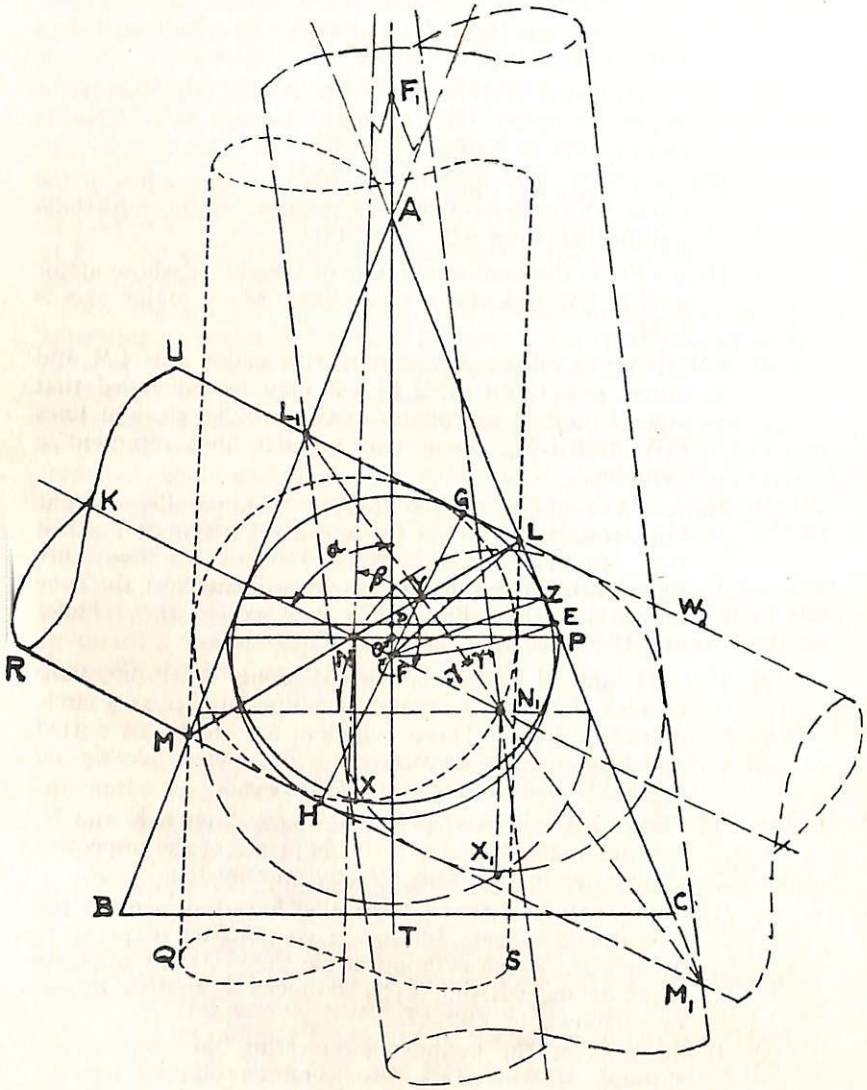


Fig. 13.

section of a cone contains two cylinders, one whose axis passes through F and the other whose axis passes through $F_1$.

(*t*) Each of the four lines drawn from F to the intersections of the cylinder with the cone bisects the angles formed at these intersections, *e.g.*, F and L joined bisects angle GLZ.

(*u*) If the cylinder runs into the cone such that one of its sides passes through the vertex of the cone and continues along the side AC of the cone (*i.e.*, the axis of the cylinder is parallel to a side of the cone), then the points G and Z will coincide and become L.

(*v*) This common point will be the foot of the perpendicular from the point F to the side AC of the cone, and the line joining L to the other point M common to the cone and the cylinder will decide the ellipse section.

(*w*) Y is the intersection of the sections ML and $M_1L_1$. Z is the point of contact of circle GZH with AC. ZY produced cuts cone axis AT at right angles and the other tangent point corresponding to Z.

(*x*) Point Y always lies on the diameter GH of auxiliary circle GZH.

(*y*) If a circle is inscribed in triangle ALM it touches ML at a focus of the ellipse of which ML is the major axis. The circle touching sides BM, ML and LC touches ML at the other focus.

(*z*) If the angle BAC of the cone becomes so very small that in the limit BA and CA meet in infinity, the cone becomes a cylinder. It will be then found that much of the above references will still apply while others will automatically cancel out, merge or disappear. The cylinder is a special case of the cone.

* * * *

The problem of joining two pipes of different diameters (see Fig. 4) can now be approached. The method given in Fig. 14 can be applied in this case. Let the larger pipe be cut across at right angles to its axis by the line BC. This normal section is a circle and is projected on the end view (left-hand side) as an ellipse. The end view of the smaller pipe is now shown, and tangents common to this circle and the ellipse are drawn. These tangents meet in a point on the centre line of the large pipe. This point is now projected on to the right-hand view as A, which is joined to B and C. Thus ABC is the interposed cone, serving the same function as the cone shown in Fig. 11. The small pipe will cut this cone in

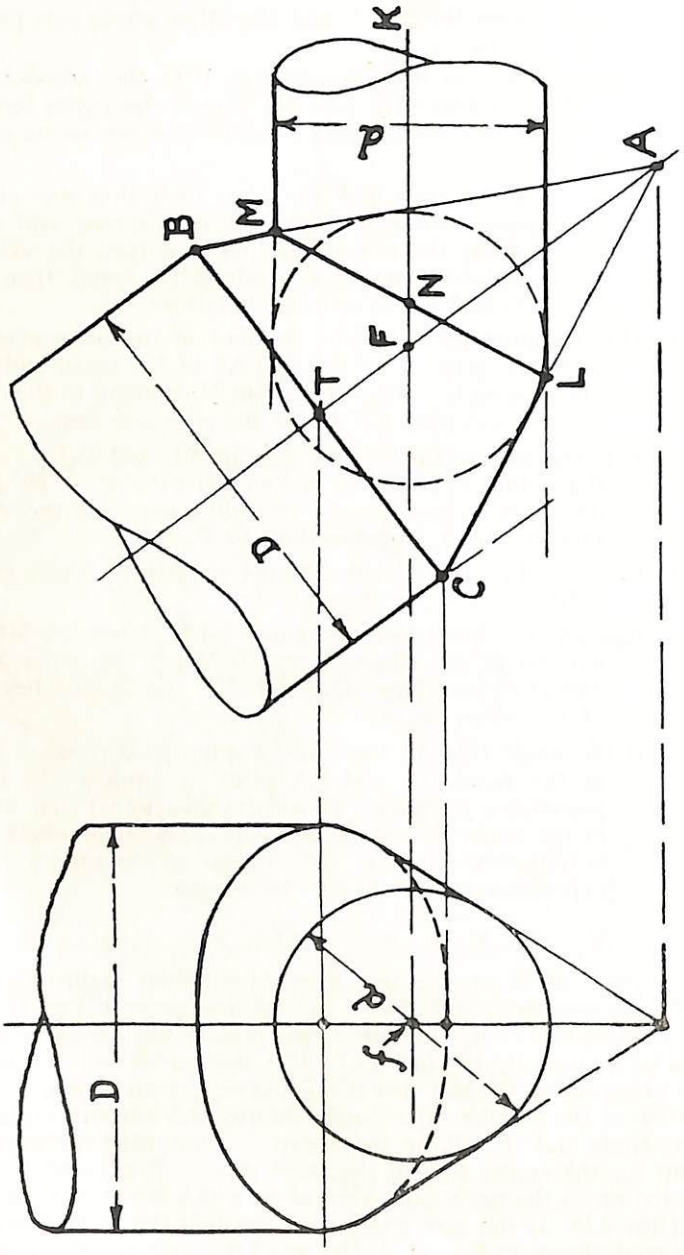


Fig. 14.

points M and L and the intersection of this pipe with the cone will be the straight line ML, the true forms of section of both the cone and the cylinder being the *same* ellipse. Hence the large pipe joins the cone at BC as a perfect circle and the cone joins the smaller pipe as a perfect ellipse at ML and so the problem is solved.

But this solution is cumbersome and roundabout in practice, and can be simplified as follows :—Let a circle of diameter *d* equal to that of the small pipe, be drawn with its centre F on the axis AT (Fig. 14) where this axis intersects the axis of the small pipe. It will be seen of this circle (1) that its centre F is the projection of the centre of the end view *f* of the small pipe ; (2) that it will touch the two sides AB and AC of the cone ABC as well as the sides of the small pipe.

The projection on the left-hand side is thus unnecessary, and all that is required is to draw a circle of diameter equal to that of the smaller pipe at the intersection of the axes of the pipes. The cone can be found by tangents and the section ML gives as the true view an ellipse. See Fig. 13, note (*o*).

The above construction has been explained in terms of the interposed cone formed with its base on the normal section BC *on the large pipe*, but the construction applies also if the normal section BC is made on the *small* pipe. The auxiliary circle of diameter D (instead of *d*) and the sides of the cone AB and AC which are tangents to this circle are produced to cut the *large* pipe at L and M. The figure required for this explanation is not shown, but it can easily be constructed to these given conditions. Do it.

Fig. 15 illustrates a special case : two solutions are shown superimposed, one based on the normal section of the larger pipe shown in full lines, and the other based on the normal section of the smaller pipe shown dotted. In this case the normal section of the *small* pipe passes through B where the top sides (*i.e.*, lines) of the pipe intersect. The auxiliary circle (shown in full line) with centre F, has its diameter equal to that of the *large* pipe. A tangent from B to this circle cuts the axis of the small pipe in A. The tangent from A passes through C, the other end of the normal section, and cuts the lower side of the large pipe at L. BL will be the ellipse section common to both the cone ABC produced and the cylinder of the large pipe.

If the normal section on the large pipe is preferred (*i.e.*, $BC_1$) the auxiliary circle (shown dotted) must be made to the small diameter and the vertex of the cone falls on the axis of the large pipe. The remaining construction follows the same method in both cases, but the results are different, as will be seen from the full lines and the dotted lines.

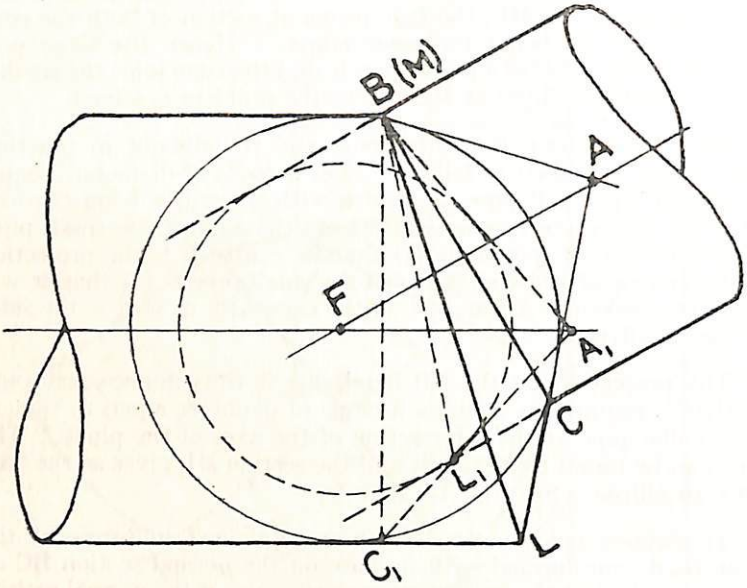


Fig. 15.

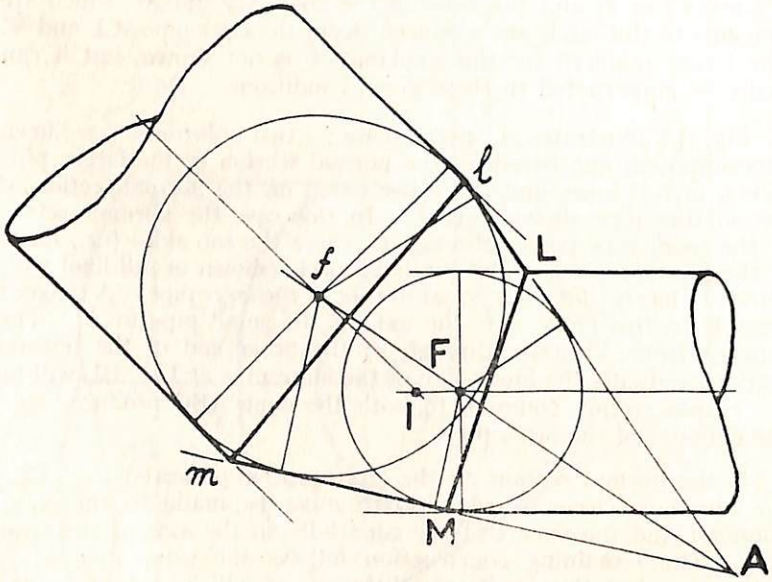


Fig. 16.

A more general case is indicated in Fig. 16. Let I be the intersection of the two pipe axes. If the auxiliary circles of both sizes are drawn to touch their respective cylinders or cylinders produced and common tangents drawn to meet in A, the cone so formed will intersect the cylinders at LM and *lm*, which will give the requisite common ellipses to enable the perfect joint to be made. This construction is of great importance.

A very interesting problem is solved in Fig. 17. It will be observed that here BC is a section taken normal to the axis of the large pipe, that is to say its true view is a circle and the bottom side of the smaller pipe runs into point C. Find the common cone and its section with the small pipe.

The auxiliary circle with centre F, the intersection of the two axes, must be made to the small diameter, for the large diameter circle would clearly fall outside the bottom side of the small pipe and so upset the condition. CL, the lower side of the small pipe, is tangent to the auxiliary circle and when produced cuts the axis of the large pipe at A. A is the vertex of the common cone, and AB, the other tangent completes the cone. Point M is thereby obtained.

The point L at the other end of the section between the cone and the small pipe can be found as follows :—The other focus $F_1$ of the hyperbola can be found in FA produced, and if the auxiliary circe is described with $F_1$ as centre and a tangent drawn from M a parallel tangent will cut the cone at L. See Fig. 13, note (*p*). It will be found that L is the point of contact between the tangent AC and the auxiliary circle, and hence FL is perpendicular to the bottom side. By reference back to Fig. 13, it will be seen that FL bisects angle ULC, and if UL coincides with AL, angle ULC will be 180° and hence angle FLA is 90°. This is expressed in note (*u*).

A special case is given in Fig. 18 in which the relative sides of the pipe are determined by the conditions. The top sides of the two pipes meet in M. The lower side of the small pipe meets the lower side of the large pipe at C, the other end of the *normal* section MC (or BC). The common section between the cone and the smaller pipe is ML where FL is perpendicular to the lower side of the small pipe. The vertex A of the cone lies also on the lower side.

While the example in Fig. 17 calls for a normal section of the large pipe from which to commence, the construction given in Fig. 19 shows a more satisfactory solution, in so far as it is much neater. The two pipe axes intersect at I. The cone is presumed to be formed by the top side of the large pipe and the bottom side of the small pipe. The vertex is thus A. Circles at F and *f* are described so as to touch the sides of the cone and cylinder or cylinder produced as at M and *l*. These auxiliary circles also touch the

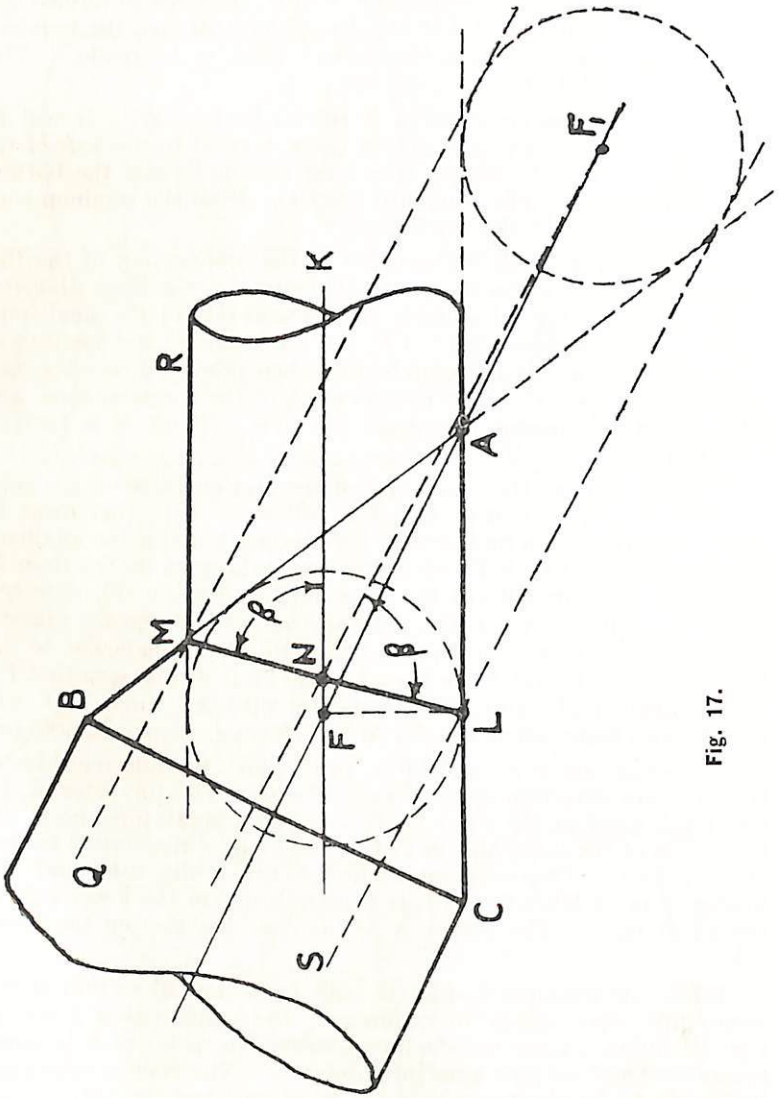


Fig. 17.

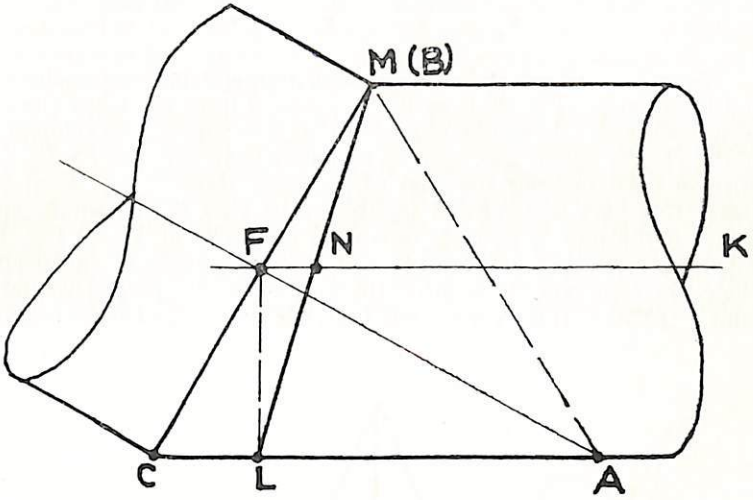


Fig. 18.

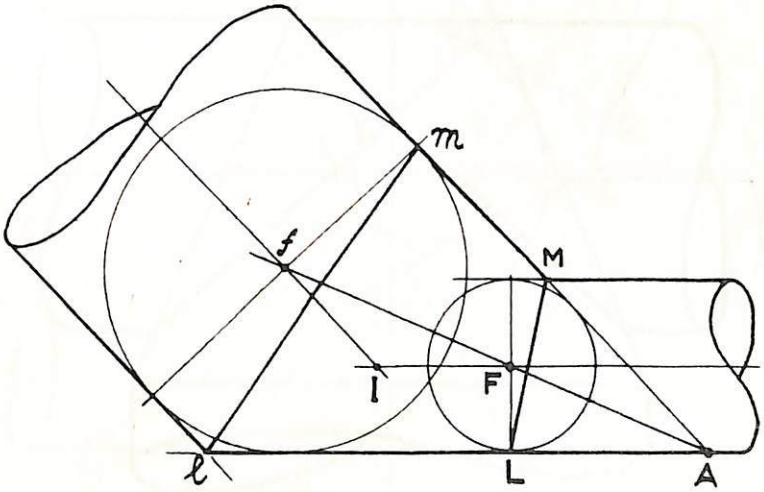


Fig. 19.

other sides of the cylinders at *m* and L (see example, Fig. 18) whence the two common ellipse sections ML and *ml* are obtained. *This case is of great importance in practical design.*

* * * *

The next problem indicates a small pipe cutting across the *end* of a large pipe. Fig. 20 is easily understood from what has already been discussed. It will be observed that it is simply a development of Fig. 11, in which this joint is repeated from the other side, but since in both sections the part of the cone above Y has been cut away, this part is displaced by the uncut part of the small pipe. Hence if the pipe is notched out, with the angle at Y, see Fig. 13, note (*w*), and the cone cut away at a similar angle at the proper place, the cone will "plug into" the pipe to form a perfect weldable joint. (*Note.*—If the cone is cut first, the small pipe can be marked

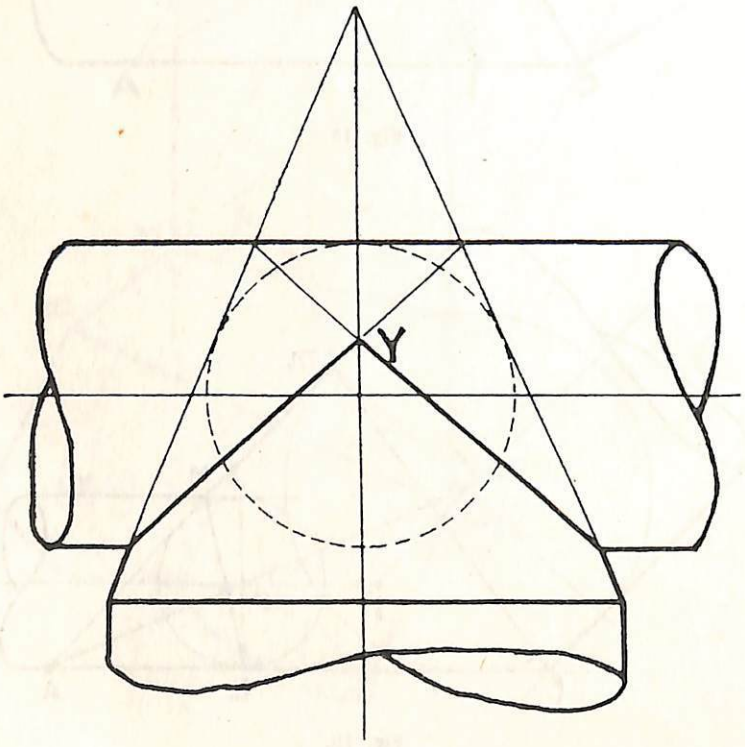


**Fig. 20.**

off to place before being notched). The construction that gives point Y should be carefully noted.

If the part of the cone *above* Y is retained and the part *below* discarded, and the combination so formed turned upside down, a conical pocket in a straight pipe is the result. This device makes a good station for a drain, the vertex of the cone being cut off and a boss for the drain fitting welded on.

Very often it is necessary to lead a small pipe from a large one, and the most common practice is to cut a round hole in the main and weld on a short piece of small pipe. There is some loss of pressure in joints of this type, although there may be compensating factors, and sometimes the joint piece is angled to facilitate the entrance of the water or the steam as an effort to reduce this loss. But it is possible to go a little bit further and guide the flow into the branch piece by means of a cone piece. Fig. 21 shows such a joint.

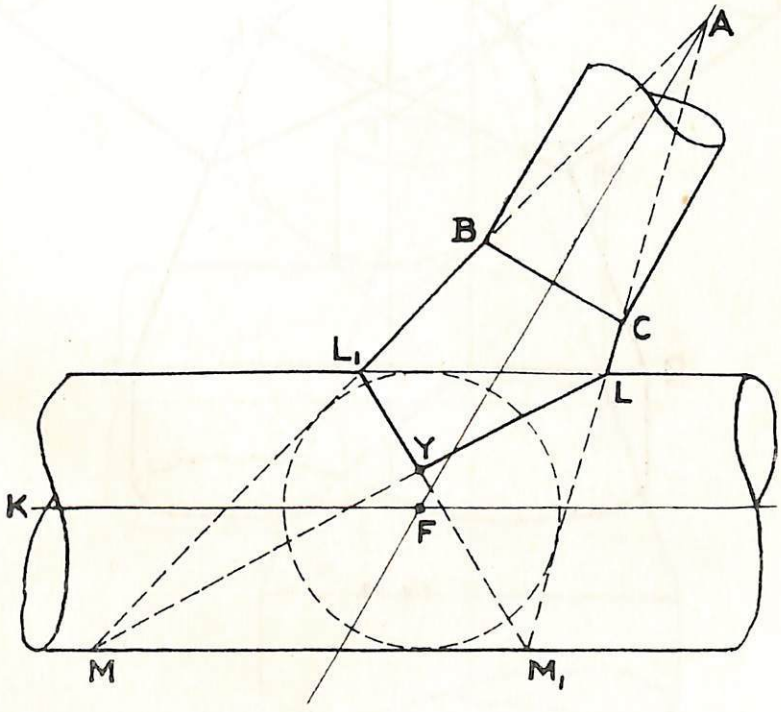


**Fig. 21.**

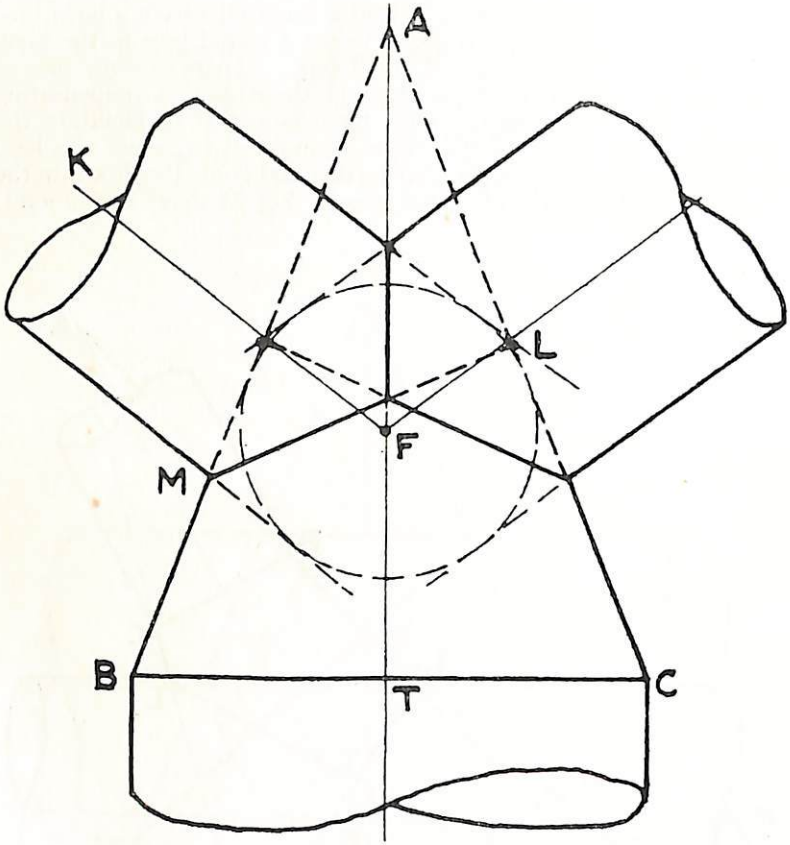


Fig. 22.

The construction can be followed by studying the reference letters and comparing them with the corresponding letters given on Fig. 13. Section LM shows one section which gives the ellipse that satisfies both the cone and the cylinder. Section $L_1M_1$ gives the other section for the cone and the cylinder. These sections intersect in Y and LY and $L_1Y$ give the parts of ellipses which meet in the line that passes through Y normal to the plane of the paper. The diameter of the auxiliary circle is equal to that of the cylinder, and its centre is F where the centre line of the branch pipe cuts the main pipe. BC being a normal section of the cone, will give a true circle of a diameter equal to that of the small pipe. This simple construction is of great service. If the large pipe is cut with a saw along the straight line LY and then along $L_1Y$ to form the notch angle $LYL_1$ it will make a perfect fitting joint with the cone similarly shaped in profile. Cut the cone first for marking off purposes.

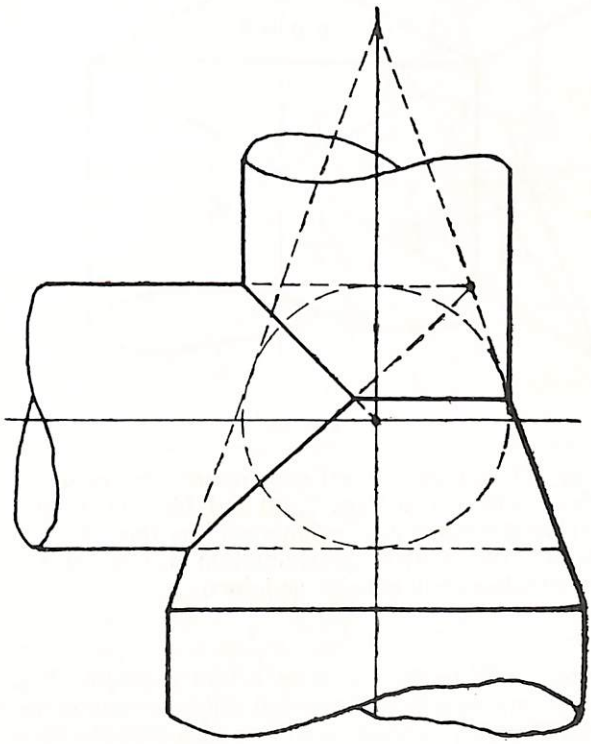

**Fig. 23.**

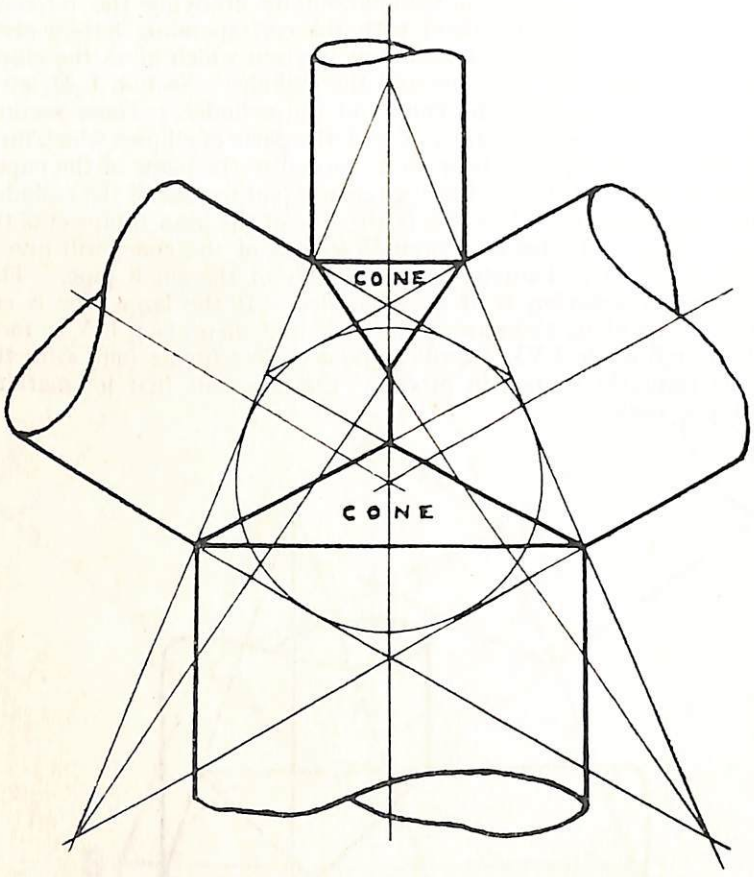


**Fig. 24.**

Figs. 22, 23 and 24 are self-explanatory, following as they do the principles outlined in Figs. 7, 10 and 14. It should be noted that several of the joints are "submerged" by the others which keep to the surface, but a little discrimination will be an ample guide to know which lines will survive as joints.

* * * *

Reference back to Fig. 21 gives a hint regarding Fig. 25. In this illustration, section *ml* gives an ellipse common to the cone and the small pipe. A scoop has been added inside the main pipe in this example. It is here shown in its simplest form as L62, but it may be made to suit the designer's fancy. The cone is cut with

a saw to give a shape 62YL$_1$, while the large pipe is cut with notch LYL$_1$. (Allowance for thickness of metal is not considered here, but the metal section can be trimmed to suit). When the cone is put in position in the main pipe, part L62 will project inside and so form the scoop. In arranging the scoop care must be taken to ensure that it will go into the opening in the main pipe. It will be seen that at point 2 the width across the opening will be the distance from 3 to 4, the auxiliary circle being the end view of the large pipe. 2 6 must be equal to or less than half 5 6, for, if more, the minor axis of the ellipse, of which 5 6 is the major axis, will not pass 3 4. The lower part 6 of the scoop may be cut off to give any area past it to suit conditions.

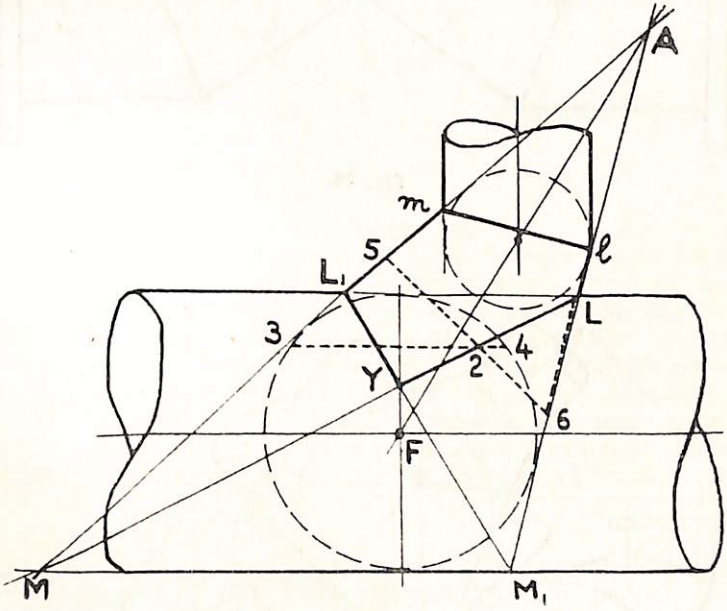


Fig. 25.

In Fig. 26 will be found a very practical solution to the Y piece. It should be compared with Fig. 22. The former makes the two small pipes from cones which join direct to the large pipe, the latter from cylinders which join an accommodation cone set in to join the large pipe. To give a closer comparison, imagine in Fig. 22 that point M coincides with B and the corresponding point on the other side coincides with C ; only a small part of the cone about base BC will be left. This result can be found by the correct choice

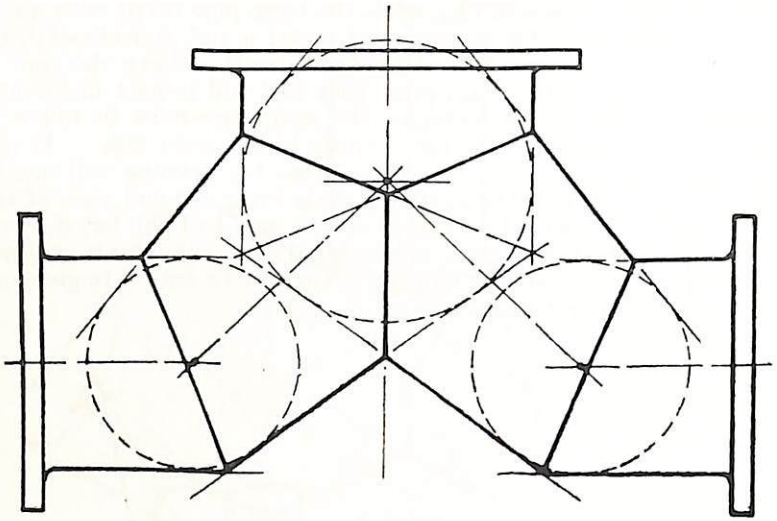

Fig. 26.

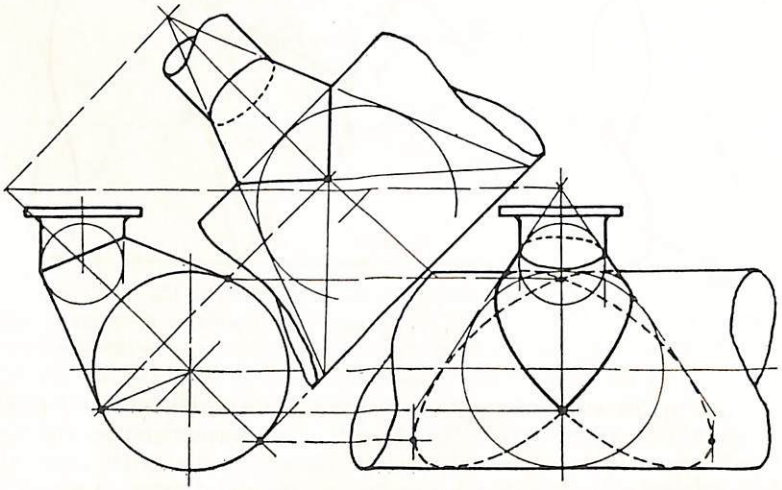

Fig. 27.

of the centre F, the angle of the cone being made by tangents to the auxiliary circle in the usual way.

In Fig. 27 another application of the cone connection between a branch pipe and the main pipe is shown. The principal point in this example is that the small cylindrical piece carrying the flange can be arranged in any plane provided it envelops the auxiliary sphere (circle).

This illustration, Fig. 27, covers also the special purpose of showing that the projections are not all so simple as the straightforward projections expressed in the preceding examples. In many cases, in practice, the projections do not show the "saw-cut" as straight lines owing to the angles of projection. To get the simple construction it is necessary to resolve the centre line of the cone connection on to the plane of the paper, and the "saw-cuts" being thus obtained all the points required for the projection can be marked off. Incidentally, in cases giving "saw-cut" notches where the view of the joint is not normal to the plane containing the cone and the main pipe, it may be remarked that the notch is made up of the intersection of two ellipses and will be viewed as two *partial* ellipses meeting in two points. This is shown by the dotted lines in the example.

It is a very simple matter for the cone branch to be set in its correct position on the main pipe. After the cone branch has been shaped by means of the two saw cuts to form a wedge it will fit the main pipe at the designed inclination of the axes in the plane common to both branch and main. It is also the case that the branch can be moved round the circumference of the main and still maintain the designed angle, the horns of the wedge being "astraddle" the main. Hence when the cone is adjusted in this manner on the *uncut* main, it is a simple matter to scribe the position on the main, which can then be saw-cut to take the cone branch for welding.

* * * *

So far only joints between cylinders and cylinders and cones and cylinders have been considered, and the matter of cones joining cones has not been mentioned.

It is unnecessary to illustrate one cone joining another cone where the finish of one frustum is the beginning of the next, each such joint being normal to the axes and consequently being a true circle. With reference to the simple case of the continuity of built-up frustums, it will be evident that such parts judiciously chosen can be arranged to give a close approximation of a sphere. Also, it is perfectly clear that if two equal cones are cut across in a similar manner by a plane the resulting ellipses are bound to coincide and a good joint can thus be made. Examples of this have already appeared in a number of illustrations.

It goes without saying that if a cone is cut across by a plane, each of the severed parts will contain the same ellipse, and as the ellipse is a symmetrical figure about its minor axis, a point already referred to, the severed parts of the cone can be assembled again *with one of each pair reversed.*

A very practical illustration of this principle is shown in Figs. 28 and 29. It is desired to construct a tapering bend from a diameter $D_1$ to a diameter $D_2$. The length of the bend (in this case a right angle bend) is laid out in a straight line as in Fig. 28. The frustum of the cone *a b l k* so formed is cut up as indicated, the sections in other cases being adopted to suit the particular fancy. Each section, with the exception of *a b* and *k l*, which are normal to the axis, will give an ellipse. As above mentioned, the ellipse *c d* of one segment will register correctly with the ellipse *d c* of the adjacent segment ; the other sections can be treated likewise. But as has already been shown—Fig. 13, note (*g*)—the minor axis of ellipse *c d* being at the mid point of the major axis, *c d* does not fall on *n* where the section cuts the axis of the cone. Hence the two points *n* do not coincide when the parts are relatively reversed ; *n* is not at the middle of *c d*. And so, in this specific instance, the centres of the major axes will continue to fall further and further inside the desired arc of the bend, until the last section arrives short of the desired position. And thus the device, successful so far, fails inasmuch as it is not positive in its results.

From a practical point of view, however, the construction can be put to good account. If, instead of the cylindrical part of the pipe (Fig. 29), section *a b* ending at the commencement of the bend, it is continued beyond it so that point *m* is outside the curve of the bend, then, provided the proper allowance has been made, the last point *s* should register with the correct position at the small end. To make the desired result more easy to attain, it is recommended that the bend should be built up from both ends by pricking out the sections from a cone drawn on tracing paper as Fig. 28, or by cutting out and arranging the different segments with alternate reversals until the best solution is secured. This may not be possible until after several trials, for it must be remembered that the least deviation from the previous attempt may give an unexpected error in the other direction. The bend being constructed by this method, it is a simple matter to reverse the operation to find the positions of the sections on the straight taper pipe, and in this way the dimensions of the segments can be very simply given. The dimensions may, of course, be given for each segment separately.

The preceding construction is essentially the practical man's device. It now remains to find some construction whereby several cones can be found so that their sections shall *all be the same ellipse.* When these frustums are found it should be a comparatively simple

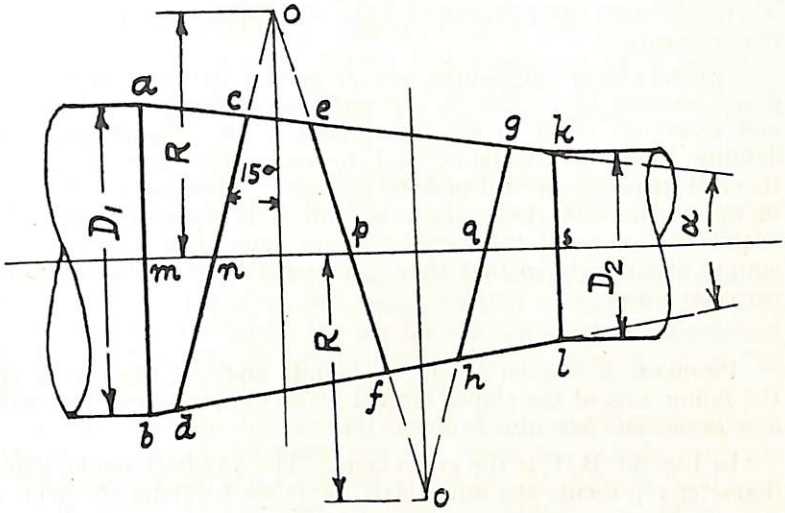
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Fig. 28.

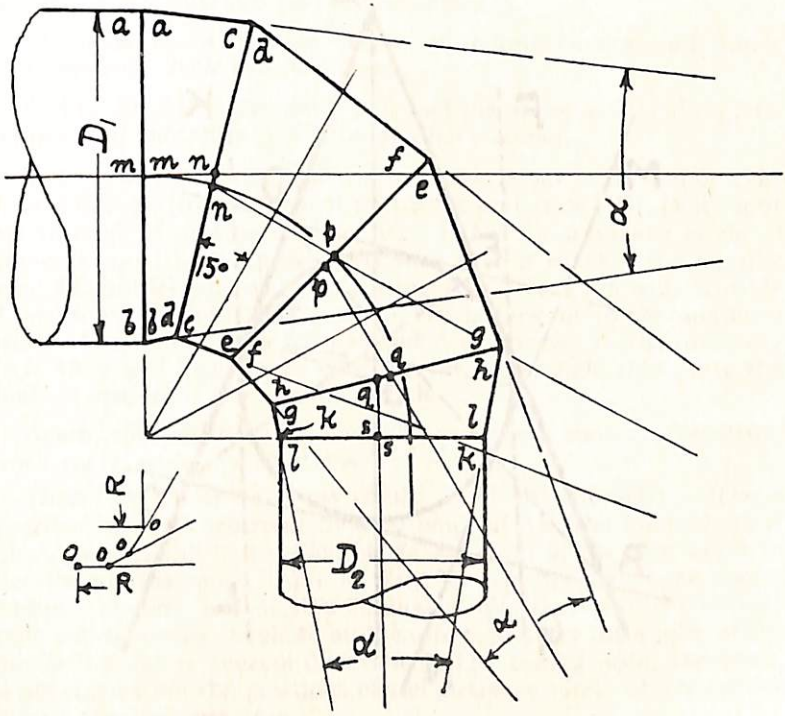
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Fig. 29.

matter to build up a curved or sinuous tapering pipe to suit given requirements.

The foregoing suggestions are of good practical value, but it is not enough to be able to cut out pieces of paper and arrange and rearrange them to get the desired result. Something more definite must be available, and to make this possible several theoretical problems will now be set out. There is a wide range of applications of these problems and it is therefore impossible within the scope of this booklet to do more than give the facts simply and clearly so that they can be fittingly applied when the occasion arises.

* * * *

PROBLEM I.—Given a cone of definite angle at the vertex and the minor axis of the ellipse formed by section, *any length of major axis is possible* (see also Problem III).

In Fig. 30, BAC is the given cone. The auxiliary circle, whose diameter represents the minor axis, is shown touching the arms of

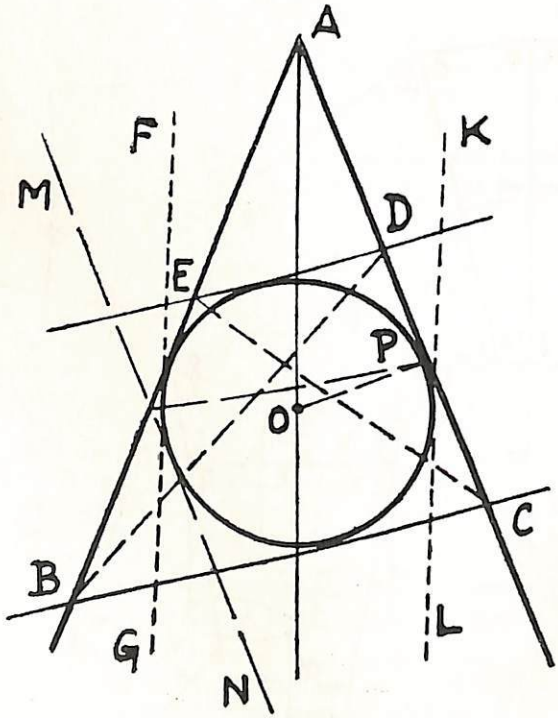


**Fig. 30.**

the cone angle internally. ED and BC are *any* pair of parallel lines tangent to the auxiliary circle and they cut the cone at E, D, B and C. Hence, from what has already been explained—Fig. 13, notes (*e*), (*f*) and (*m*)—BD and EC are alternative sections to fulfil the requirements. But ED and BC are *any* two parallels, therefore there is no limit to the number of major axes.

If the two parallel lines (as FG and KL) cut the cone angle in only one place each, then for such a condition only one section is possible.

The position of the intersecting cylinder where one side coincides with side AC of the cone, MN being parallel to AC, has only one practical solution, namely, the line joining the point of intersection of AB and MN and the point of contact P of tangent AC to the auxiliary circle (Fig. 13, Notes (*u*) and (*v*) ).

As the major axis decreases from this section, the limit is reached when it is equal to the minor axis, *i.e.*, when the parallel tangents to the auxiliary circle are parallel to the axis of the cone, and as it increases above this section the limit is infinity, *i.e.*, when MN produced cuts AC produced in infinity, and the other tangent parallel to MN cuts AB just below vertex A.

PROBLEM II.—Given an ellipse of definite major and minor axes, *any cone angle will be possible.*

In Fig. 31, AB is the major axis and the minor axis is also given (represented *subsequently* by the auxiliary circle).

With B as centre mark off arc of radius equal to the minor axis, Draw a line AC from A tangent to this arc and draw DBE (a straight line through B and parallel to AC. Draw the auxiliary circle of diameter equal to the minor axis such that it touches the parallel lines) AC and DB and also cuts the line AB. There is a wide latitude of positions, the limits being where AB is tangent to the auxiliary circle. If now tangents from B and A are drawn to the auxiliary circle they will meet in F, which is the cone angle that suits the chosen position of the auxiliary circle

Again, the position of the auxiliary circle is chosen arbitrarily, hence there are other solutions.

There are limits to these results. If the auxiliary circle is described with its centre at the mid point of AB, the tangents to it from A and B will be parallel, hence, the limit of the cone angle in this direction is zero. And, as may be expected, the cone angles obtained on one side of this "cylinder" position of the auxiliary circle will be similar to those on the other side, but the angles of the cone will point in reverse directions. The results need, therefore, be obtained from the positions of the auxiliary circle centre on one side of the sections only.

If the auxiliary circle is drawn tangent to AB, the angle AFB (this case is not illustrated) becomes so great as to become in this limit a straight line or 180°.

There is thus an infinite number of angles of cone possible when a cone is required to join a given cone at a given ellipse section.

The above construction may be freely employed when a trial and error method is followed to obtain the cone angle most suitable for the design. The auxiliary circle on such occasions is moved about until the desired result is reached. But although this method reduces the amount of guesswork it is not altogether satisfactory. The next problem is more definite in application.

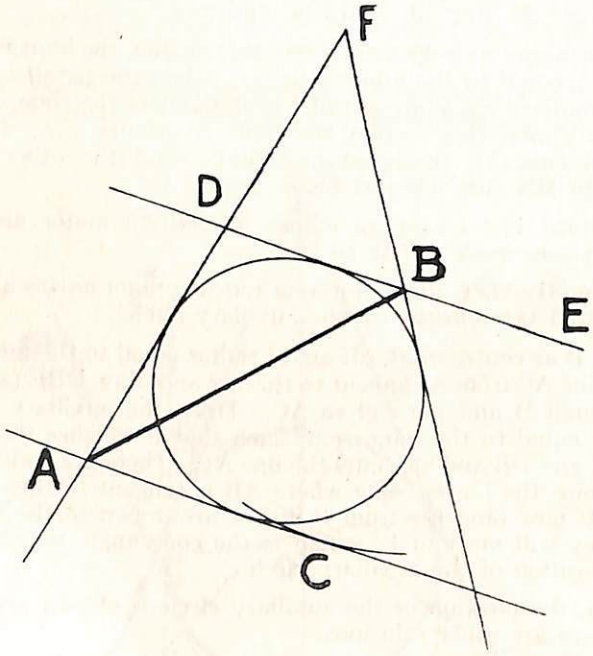


**Fig. 31.**

PROBLEM III.—Given the cone angle, the minor axis of the ellipse, and the intersection of the major axis with one side. Find the major axis.

See Fig. 31. The cone angle AFB is given, also the length of the minor axis and the point B on one side (the intersection with

the major axis). Draw the auxiliary circle, inside the cone angle, of radius equal to half the minor axis. Strike an arc of radius BC equal to the length of the minor axis. Draw the common tangent CA to this arc and the auxiliary circle to cut FA in A. AB is the length and position of the major axis.

PROBLEM IV.—Given the cone angle and the section which represents the major axis in length and inclination, *find the minor axis.*

In Fig. 32, ABC is the cone and DE is the major axis in length and inclination. The minor axis passes through the mid point of the major axis. The mid-point is F. HK is a section normal to the axis of the cone and gives a circle shown in semi-circle as HLK. Mid point F is the end view of the minor axis which lies in the plane of section HK and which will consequently be equal in length to FL, seeing that semi-circle HLK is a normal view of section HK. With F as centre and FL as radius, describe the full line circle and then draw tangents to it from D and E. These tangents represent

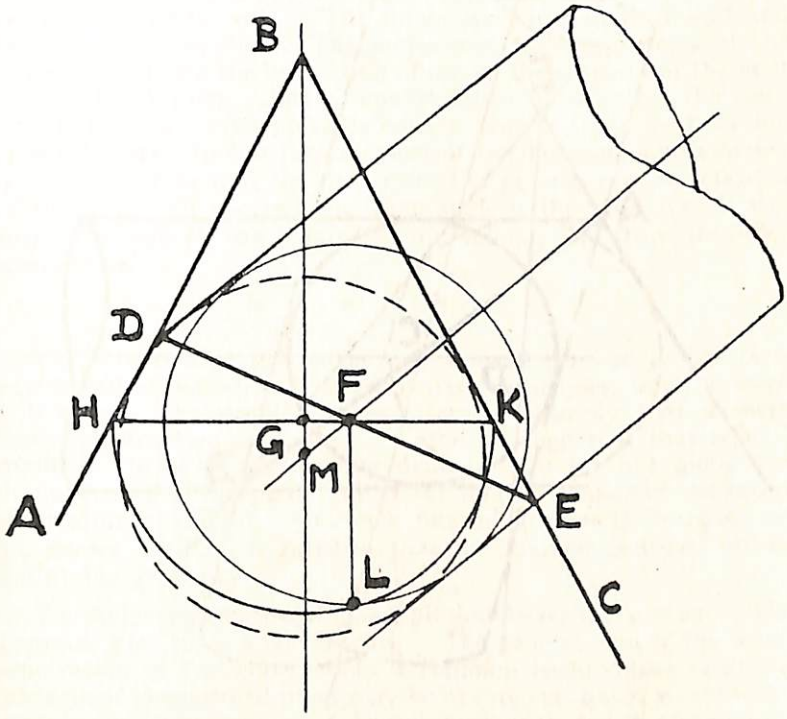


**Fig. 32.**

the intersecting cylinder, and the axis of this cylinder will pass through F. This centre line cuts the axis of the cone at M, which is the centre of the auxiliary circle shown dotted. The diameter of the auxiliary circle is the minor axis. See Fig. 13, notes (*g*), (*h*), (*k*), (*l*) and (*m*).

PROBLEM V.—Given the major and the minor axes of the ellipse and the inclination of the ellipse *surface* to one of the sides (*i.e.*, a "generator") of the cone, *to find the cone angle.*

(The inclination referred to is the angle of the side in relation to the major axis in a plane *at right angles to the plane of the section*).

In Fig. 33, AB is the major axis, the minor axis being represented by the diameter of the full-line circle. The side of the cone in relation to the major axis, representing the ellipse surface, is shown as AE.

The full circle is drawn with centre C at the mid point of AB. Tangents are drawn from A and B to the full-line circle. These

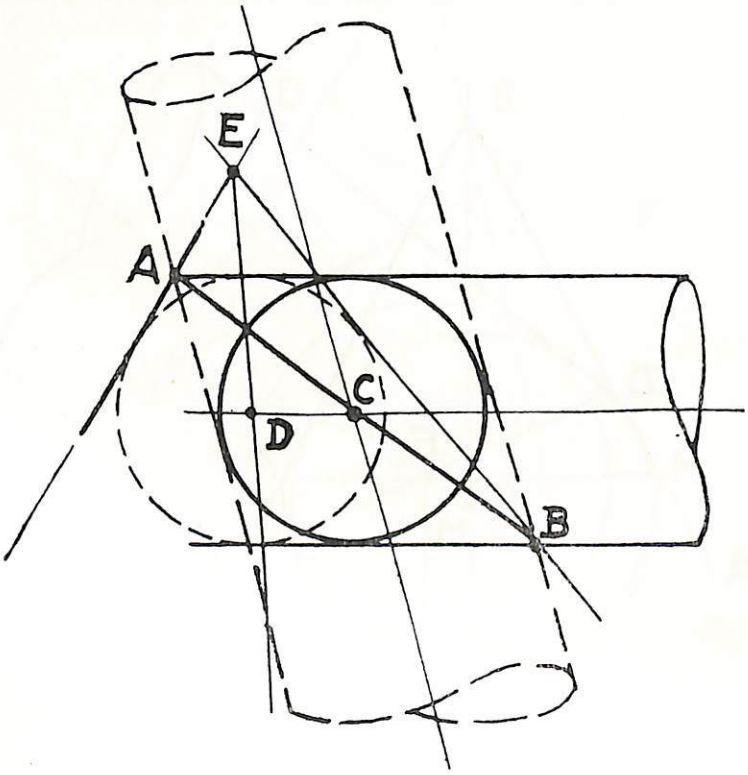


**Fig. 33.**

lines represent the intersecting cylinder and CD is in the centre line of this cylinder. A circle (shown in broken line), equal in diameter to the full circle, is described with its centre on this centre line to touch the line AE. BE is a tangent to this circle and meets AE at E. AEB is the cone angle, in its position relative to the section (major axis) AB, while the circle with centre D (*i.e.*, the intersection of the cone axis and the cylinder axis) is the auxiliary circle.

* * * *

The preceding problems give the methods whereby a tapering bend can be assembled without resort to trial and error, but a certain amount of judgment must be exercised to give the most satisfactory results. Any assembly of parts made on the above principles, however, will give correct joints, but experience counts a great deal in knowing exactly how to approach the problem in hand.

Take Fig. 29 as a general example. Start off with segment *a b d c*. The cone angle is known, so are the section *c d* and its inclination in the cone. The minor axis has to be found and Problem IV is applied. The major and the minor axes of the ellipse now known the inclination of one of the sides *d f* of the next cone is fixed upon. Apply now Problem V whereby the next cone joined up to the previous cone is found. The next section *e f* is arbitrary—to suit the judgment of the designer—and starting again with *e f* to find the next cone the process can be repeated indefinitely. Of course if the cone angle is the same for all segments Problem IV can be applied throughout, and there are other possibilities.

* * * *

The construction just given for a conical bend is, as has been demonstrated, based on true geometrical principles, but the work is tedious. The results, however, seem to imply that a more direct construction is possible. Let it be suggested that several auxiliary circles of diminishing diameter are set out along the circumference of the curve and let the joints be made at the interpenetration of the adjacent cones, but this cannot be accepted by the reader until he is satisfied that the method is based on an acceptable geometry.

The following notes will dispel all doubts on the matter. The diagram, Fig. 13, is a special case. The general case is the interpenetration of two cones about a common basic sphere, and the subsequent geometrical proof may be of interest, but it is necessary to state that its acceptance is based on the fact that in any quadrilateral circumscribing a circle the intersection of the diagonals

coincides with the intersecting point of the diameters joining the opposite tangent points. The geometric truth follows on the Ceva and Menelaus theorems (see also Appendix 1 for another proof). The diagonals referred to are the two plane sections common to both cases.

Let two cones DAF and FBE, Fig. 34, interpenetrate such that each exactly contains the basic sphere HKGL whose centre O is on the intersection of the axes of the two cones. The respective profiles of the cones cut each other at F, D, C and E. The figure FDCE is the quadrilateral circumscribing the circle referred to above, H, K, G and L being the tangent points and M the point common to the four intersecting lines.

It is evident that KL will be at right angles to the axis AO and will consequently intersect the cone DAF to form a cylinder section having KL as diameter. Similarly the section GH will give a circular section of cone FBE. Hence if the circular sections are projected as circles KPL and HNG on to the plane of the paper, and lines MP and MN drawn at right angles to KL and GH respectively, these lines will penetrate the respective conical surfaces. It remains to prove that these two lines are equal so that it may be known that at their distance above and below M the cone surfaces coincide. This equality can be proved, for, since KL and GM are straight lines, $MP^2 = KM \cdot ML$ (in circle KPL) = $GM \cdot MH$ (in circle HKL and circle HNG) = $MN^2$ (in circle HNG), whence MP = MN.

But in any cone a section inclined to the axis and not parallel to a side (profile) cuts off an ellipse. Hence section DE cuts off an ellipse in cone DAF and another ellipse in cone FBE. Here, then, are two ellipses having the same major axis. But these two ellipses have a fixed common point in their respective circumferences above point M (MP = MN above) on their equal major axes. And if a figure is known to be an ellipse, and the major axis is known, and also a point in the circumference is known, then there is only one solution and the ellipse can be constructed. See Appendix 2. It is evident then that both cones have the same ellipse of section. That is to say the joints of the two conical surfaces will register exactly—even in reversal, a point worth remembering.

Now on line DE describe a semi-circle DRE with centre at Q and draw MS perpendicular to DE and equal to MN and MP. Produce MS to cut the semi-circle at R. Join QR. Through S draw ST parallel to DE to cut QR at T. Then QT is the *semi-minor axis* of the common ellipse of section while DE is the major axis. See Appendix 2. It can be proved that the minor axis thus obtained is *not* equal to the diameter of the basis sphere (or auxiliary circle). It is not constant as in the special case of the

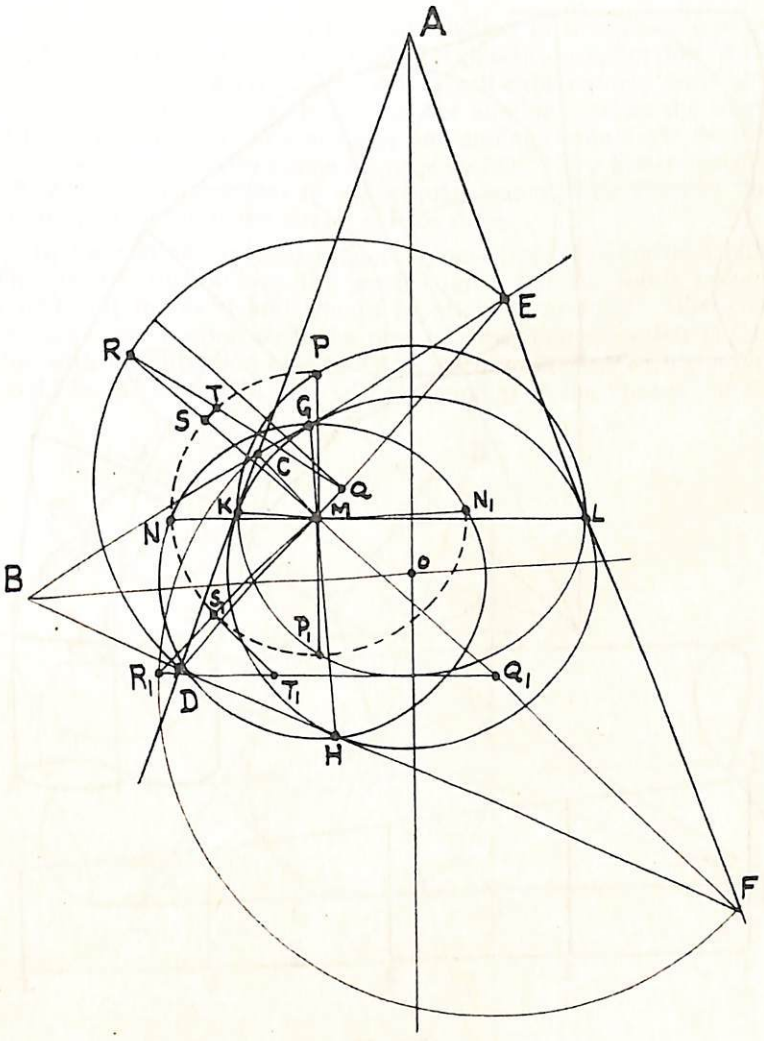


Fig. 34.

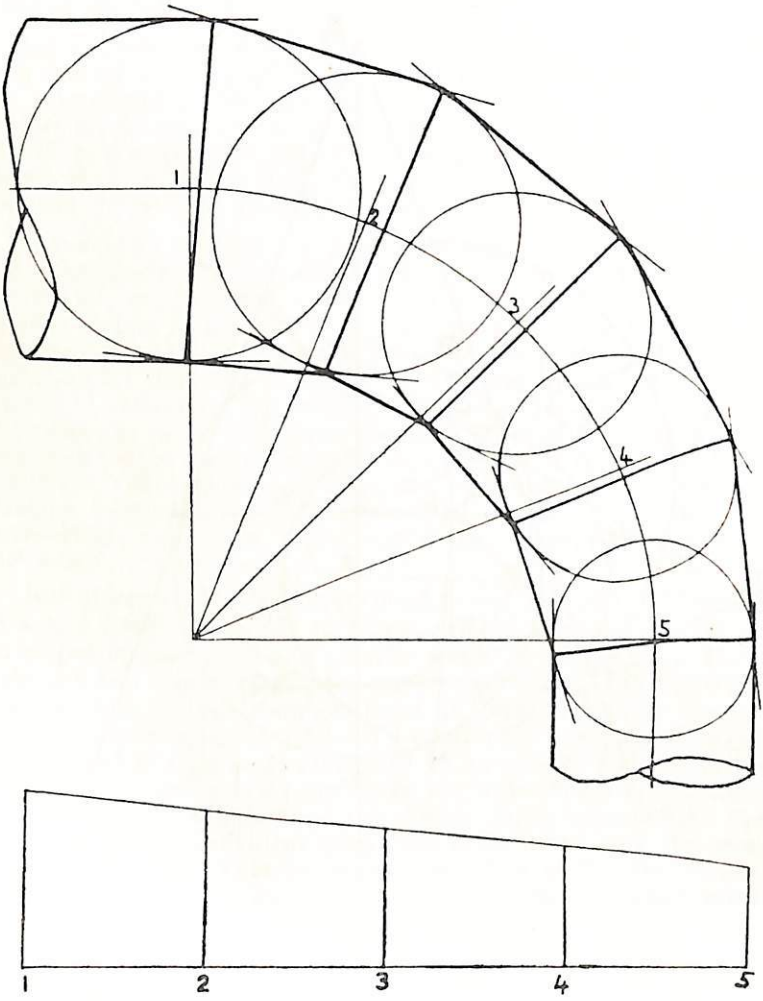


Fig. 35.

interpenetration of the cylinder and the cone. (A similar proof applies to section CF and the semi-minor axis in this instance is $Q_1 T_1$).

* * * *

Now that confidence in the construction of a conical bend by auxiliary circles has been established a practical application of the principle can be given. Fig. 35 is self-explanatory, but as a suggestion for regulating the sizes of the auxiliary circles the length of the arc is laid out in a straight line and the cone angle decided upon (not to scale—to economise page space). The linear spacings 1-2, 2-3, etc., correspond to the angular spacings for the arc, and the individual auxiliary circles can be drawn.

In Fig. 36 two conical branches come from a cylindrical pipe. The construction follows the usual course, but the joints become a little bit involved and should be studied carefully. For cone OC alone one section with the pipe is EF, while the other is GH. But with the intrusion of cone OD alone the sections with the pipe would be KL and MN. It will be found that the "horns" of the

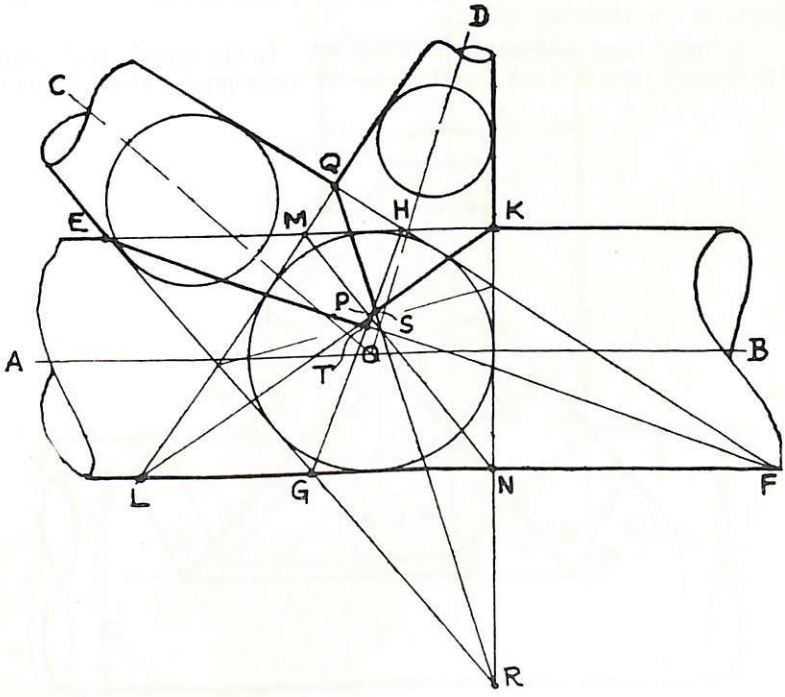


Fig. 36.

cones run together and join in the section QS since the auxiliary circle in the cylinder is common for both cones. (If the auxiliary circles did not have the same centre O the result would be different). The "cut-out" from the pipe would follow along lines ETPSK.

* * * *

The subject just outlined lends scope for much greater development, but if sufficient interest has been aroused to stimulate a wider use of these devices in the drawing office some success has been attained. The use of the cone in pipework is not by any means unknown ; in ventilation engineering its application is very common, but there are other applications where pipe work is an incidental and consequently is often liable to be overlooked. It is for those who are not acquainted with the use of cones in this way that this information has been collected, evolved and presented.

* * * *

In order to round off the subject of pipe joints it may not be altogether out of place to illustrate briefly one or two constructions which may be of some value in plate work, or even pattern shop practice, not to mention approximate visualisations of machine parts in the drawing office.

A "tee" joint is illustrated in Fig. 37. In the usual "tee" joint the branch pipe is stuck direct on to the main pipe. If the branch

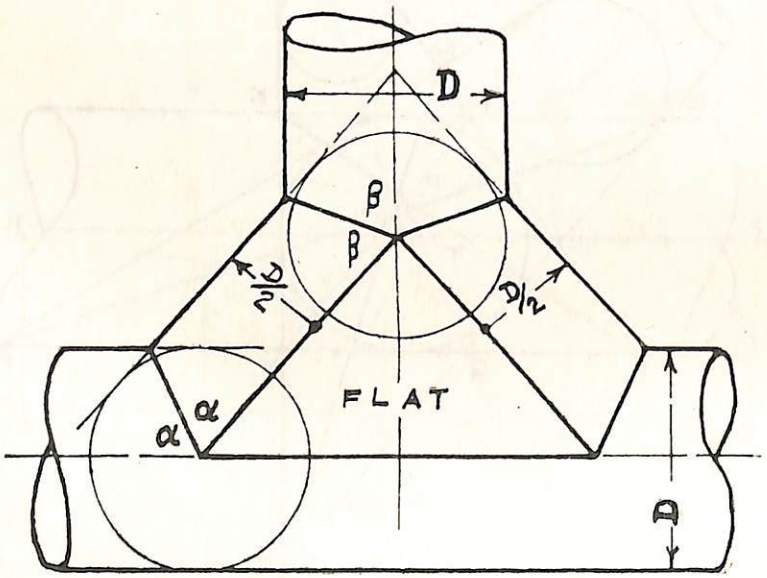


Fig. 37.

piece is smaller than the main pipe, devices illustrated in Figs. 21 or 25, or variations of them, can be employed, but in the present instance the two pipes being the same diameter a special construction is possible. Here the cone gives place to the cylinder, or parts of the cylinder. The shoulders of the base piece are pipes cut lengthwise in two, and the filling-in pieces are flat triangular plates. This construction overcomes the congestion at the entrance to the branch piece and it is an improvement, when cost is not the main factor, on the conventional "tee" joint.

When the main pipe is larger than the branch the half-cylinders can be replaced by half cones and thus another construction that might have been illustrated along with the others is put on record. It is worthy of notice.

Fig. 38 is a slight variation of the previous "tee" joint. And if the main pipe comes to an end the branch could be made to the dotted lines. Or, again, if the sharp corner so formed is objected to, it could be cut off and a half pipe, shown in broken line, substituted parallel to the inner piece but still giving a flat "cheek" between to ensure that the normal section at the bend is greater than the bore of the pipe.

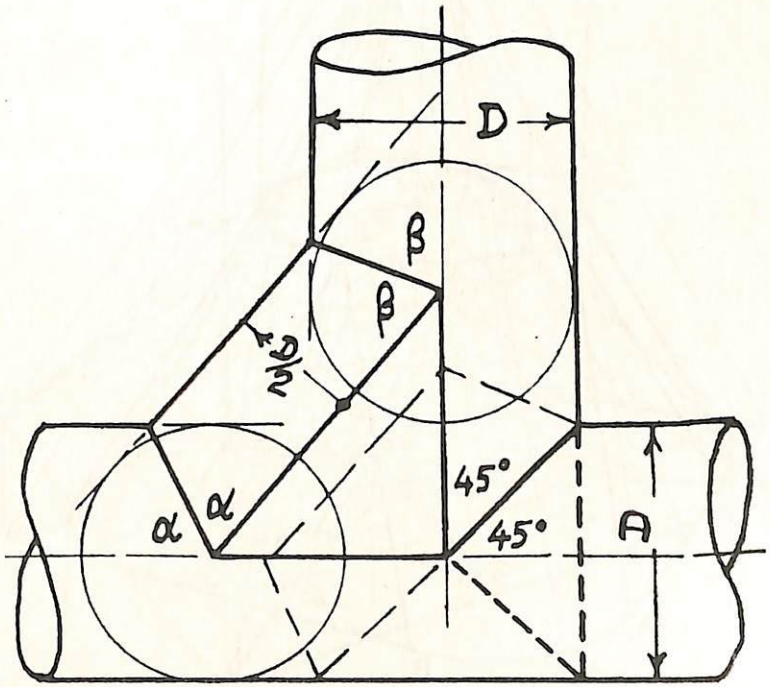


Fig. 38.

Other designs will readily occur to the reader.

Another type of construction is shown in the next three illustrations which indicate forms for the change of section from circular to square pipes and vice versa. These diagrams are in perspective and all the necessary constructional lines are indicated or suggested.

In Fig. 39 a design is given in which a square presents a support to a cylindrical pipe. The corners of the square are removed and rounded to a radius equal to that of the top cylinder. In this way an oblique cylinder shown by the dotted lines is formed, one suitably selected quarter of it AOB—$A_1O_1B_1$ forming the corners. The filling-in pieces at the sides are flat. In the figure $V_p$, $V_s$ and $V_c$ are the vertices of the lines of the pyramid, the sides, and the

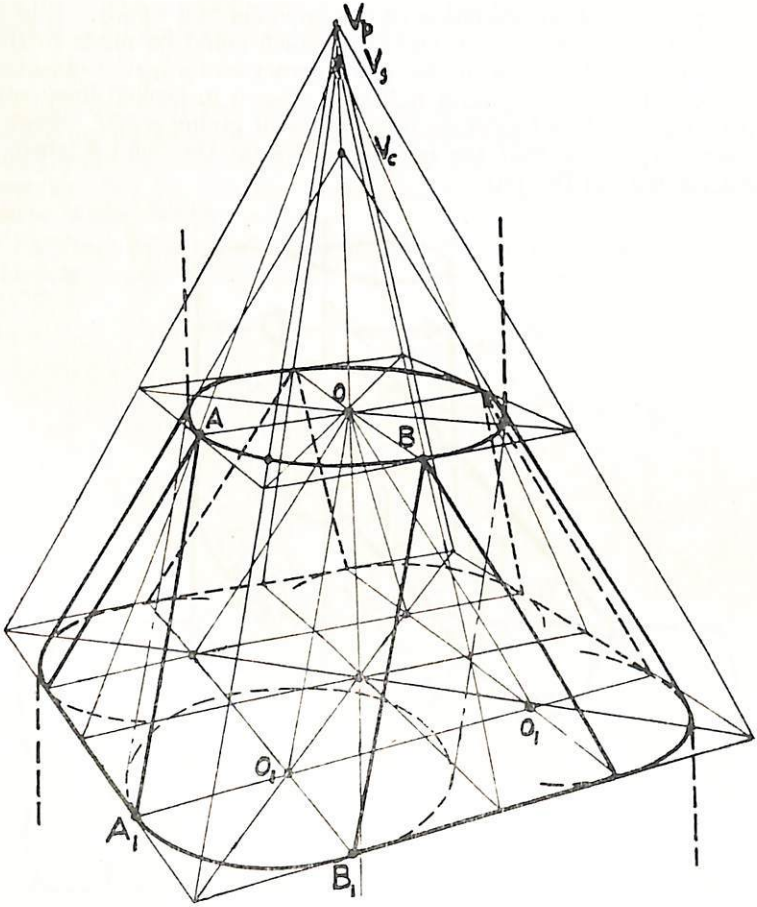


Fig. 39.

cylinder, respectively. It is clear from this construction that there are no sharp corners anywhere on the sloping walls, and every horizontal section of the structure is definitely known, seeing that it has been made according to a known law. This last-mentioned feature is a very desirable one from the designer's point of view—he knows where he is—and the workman in the shops is not left to his own devices to work the shapes together. This remark applies also to the next two designs.

If it is preferred that the corners of the square base should be retained, then the oblique cone (inverted), Fig. 40, is used instead of the oblique cylinder. In this case $V_p$, $V_s$ and $V_c$ represent the convergence of the boundaries of the vertical sections of the pyramid, the sides and the inverted cones.

When a circular bore pipe has to be changed to a square pipe, it is a common practice to form the piece as if it were a cylinder

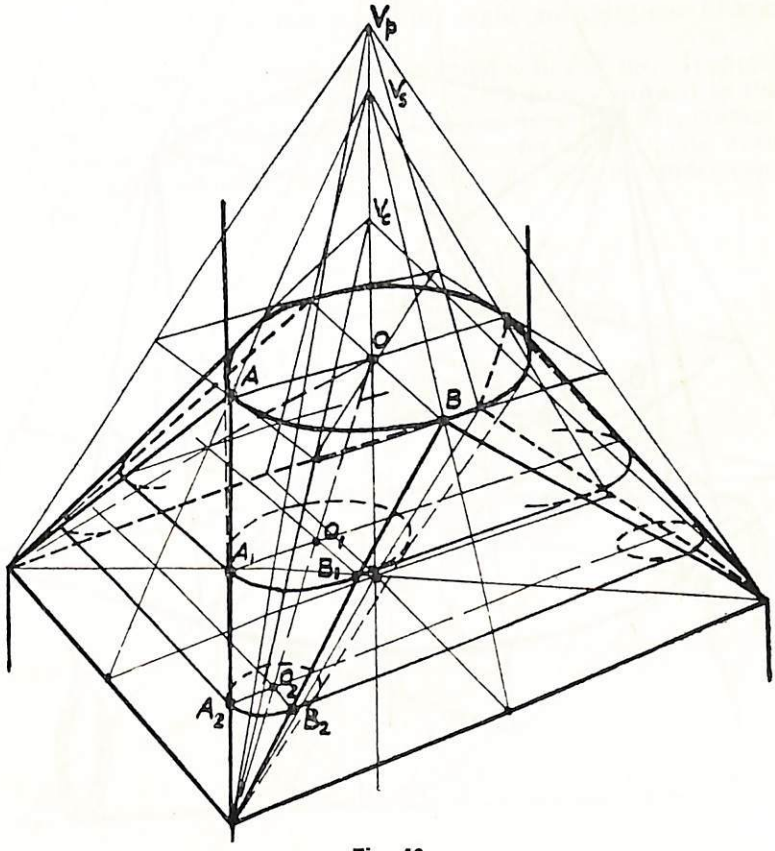


**Fig. 40.**

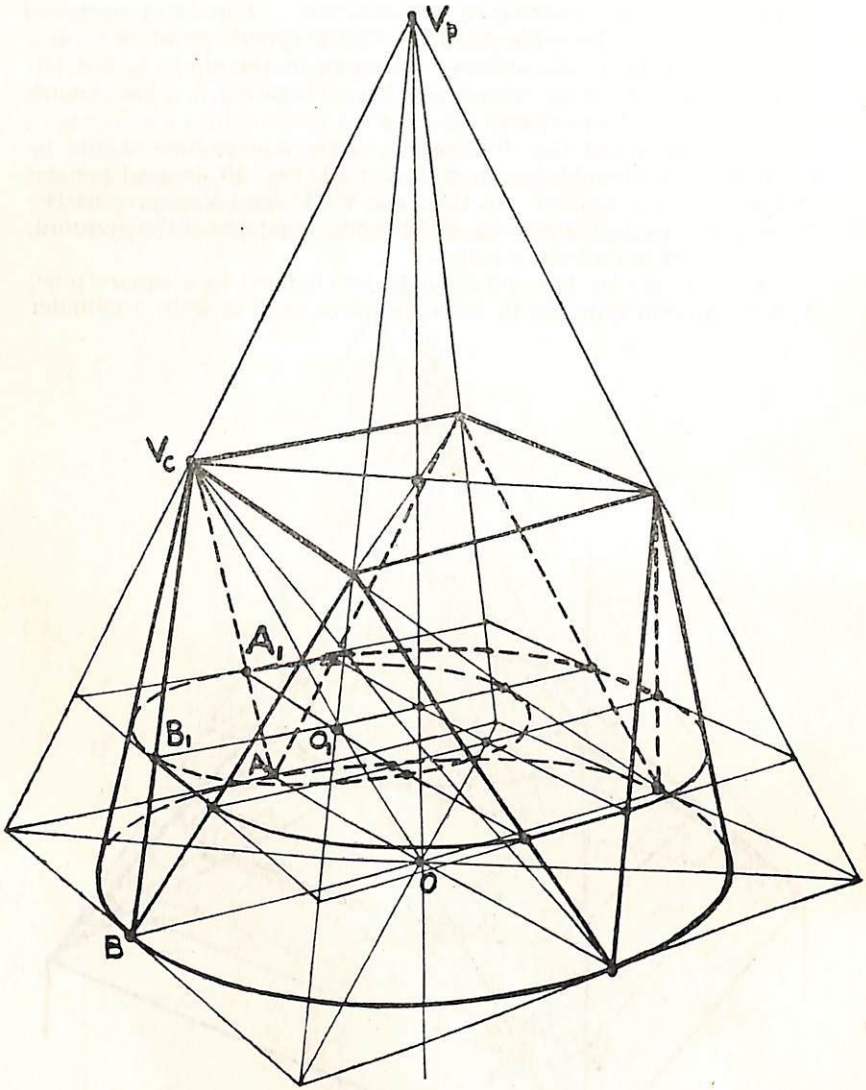


Fig. 41.

sliced by four planes which start from the sides of the square and touch the circle at the bottom. A cone can be used if the cylinder is not suitable, but the cylinder is chosen to simplify explanation. In either case this is quite effective, but the general appearance can be distinctly improved upon, for the sides are marred by the resulting sharp corners.

The improvement is indicated by Fig. 41. Here no sharp corners appear at the sides. The cross-section changes *gradually* from the circular base to the square top, as may be observed from the arbitrarily taken horizontal section indicated by the heavy line. This varying section is attained by the use of the requisite parts of the oblique cones all based on the ground circle, and triangular plane pieces filling in the spaces. This case, Fig. 41, does not differ fundamentally from that shown in Fig. 40 The construction holds good whatever may be the relative sizes between the circle and the square, nor must it be a square only, for any plane rectilineal figure can also be treated in this way with slight modifications to suit conditions.

Fig. 42 should be viewed in conjunction with Fig. 25. It shows how the principles set out above can be effectively utilised in the construction of wooden patterns with the use of a little imagination. In a similar way the other examples given for welded plate work can be readily adapted to suit the particular articles under construction.

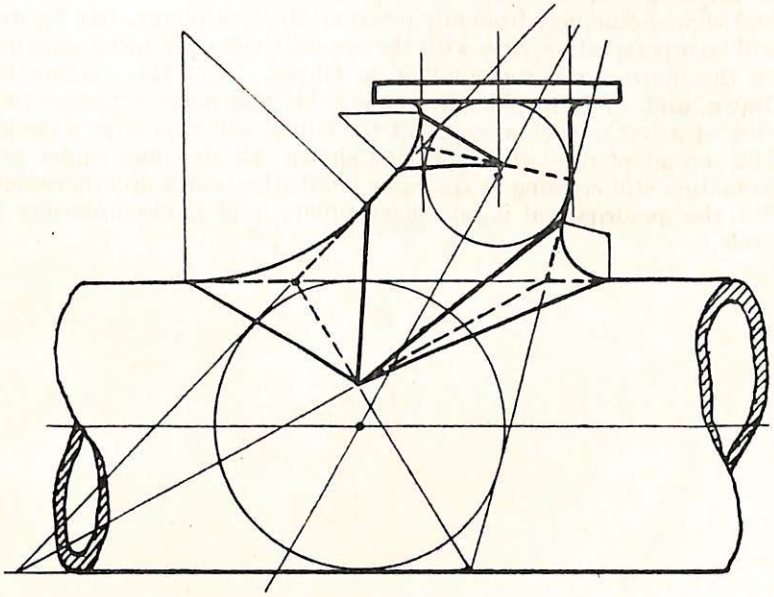

**Fig. 42.**

## Appendix I.

Any quadrilateral ABCD circumscribes the circle HEFG, which letters are the tangent points. Prove that the lines AC, BD, EG and HF all pass through one point.

Let a circle be inscribed in a square lettered as given. Fig. 43. It is known to all that the diagonals and the diameters in this figure cross at a point, the centre of the circle. As no dimensions are involved a piece of commonsense from projective geometry can be invoked. If the square-cum-circle diagram is laid on the table and viewed obliquely from any position, the first picture (see figure) will be a perspective view with the opposite sides produced meeting on the horizon and surrounding an ellipse. Let this picture be drawn, and, in turn, place *it* on the table and make a perspective view of it but in such a way that the ellipse will appear as a circle. The second picture will appear as shown, all the lines under examination still crossing at the same point (they can't do otherwise). But the quadrilateral is no longer square, and it circumscribes a circle.

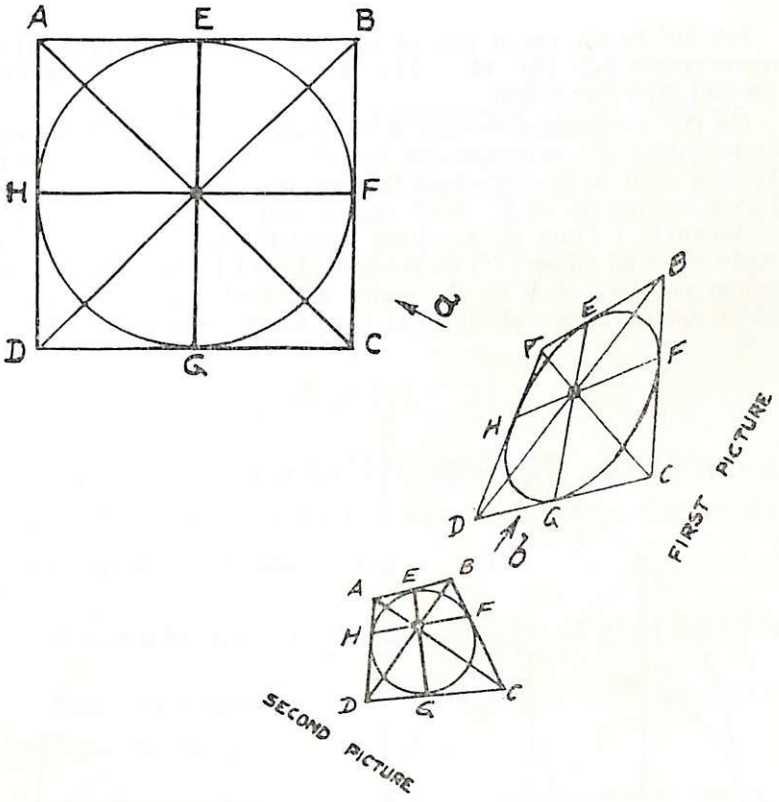
A
E
B
H
F
D
G
C
a
A
E
B
F
H
C
D
G
a
FIRST PICTURE
A
E
B
H
F
D
G
C
SECOND PICTURE

Fig. 43.

## Appendix II.

Let DE be the major axis of an ellipse and S a point on the circumference (see Fig. 44). The problem is to find the minor axis and draw the ellipse.

On DE as diameter describe a semi-circle, the centre being Q. From S draw SM perpendicular to DE, and produce MS to cut the semi-circle in R. Through S draw ST parallel to DE. Join Q to R cutting ST at T. With centre Q and radius QT describe a semi-circle. From the resulting figure the familiar method of constructing an ellipse will be recognized, and by the selection of various positions of R on the major semi-circle various points S can be found, thereby plotting out the circumference of the ellipse.

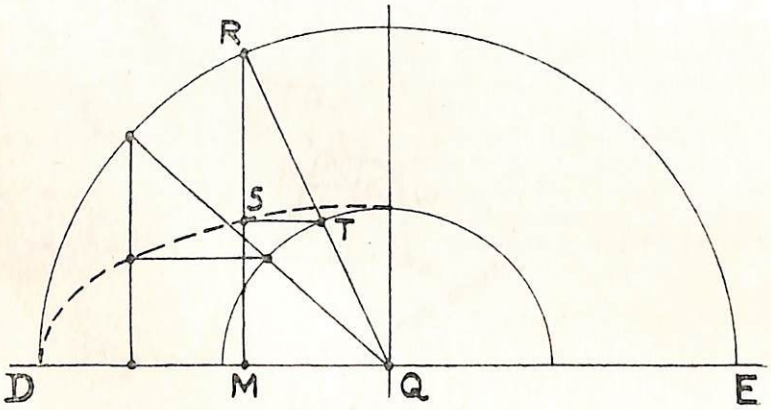


Fig. 44.

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23. $1''$ ,, ,, ,, ,,
24. $\frac{3}{4}''$ Square Steel Tubes as Struts (30 ton yield).
25. $\frac{7}{8}''$ ,, ,, ,, (30 ton yield).
26. $1''$ ,, ,, ,, (30 ton yield).
27. $\frac{3}{4}''$ ,, ,, ,, (40 ton yield).
28. $\frac{7}{8}''$ ,, ,, ,, (40 ton yield).
29. $1''$ ,, ,, ,, (40 ton yield).
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31. Moments of Inertia of Built-up Sections (Instructions and Examples). } Connected.
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54. ,, ,, ,, (Round Wire). } Connected.
55. ,, ,, ,, (Square Wire).

56. Relative Value of Welds to Rivets.
58. Graphs for Strength of Rectangular Flat Plates of Uniform Thickness.
59. ,, Deflection ,, ,, ,, ,, ,,
61. Deflection of Leaf Spring.
62. Strength of Leaf Spring.
63. Chart Showing Relationship of Various Hardness Tests.
64. Shaft Horse-Power and Proportions of Worm Gear.
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66. ,, ,, ,, ,, (Tengantial Stress) }
67. Hub Pressed on to Steel Shaft. (Maximum Tangential Stress at Bore of Hub).
68. Hub Pressed on to Steel Shaft. (Radial Gripping Pressure between Hub and Shaft).
69. Rotating Disc (Steel) Tangential Strain. } Connected.
70. ,, ,, ,, Stress. }
71. Ring with Uniform External Load, Tangential Strain. } Connected.
72. ,, ,, ,, ,, ,, Stress }
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75. Ring Oil Bearings. }
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